Department of Electrical and Computer Engineering

Improving Power Transfer Capability of SCIG based Fixed Speed WECS

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Declaration

"To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university"

Signature: ___________________________

Susanne Christina Sugiarto

Date: 20th April 2015

This thesis is dedicated to my parents and my other half.

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Abstract

Wind power generation is regarded as the most promising source of all renewable energy system to meet the global commitment to combat climate change. In this research, a concept to advance the knowledge in the possibility to improve the power transfer of the fixed speed wind energy conversion system based on a squirrel cage induction generator is presented. The proposed system endeavour to increase power extracted from the wind energy system and yet is simple as it does not call for the utilisation of any power electronic converter to facilitate the interface between the induction generator and the grid. On the other hand it proposes an design to utilise the existing variable capacitors and tap changing transformer that are already part of the wind conversion system with a new control algorithm.

The utilization of variable capacitors and tap changing transformer in tandem can improve the power transfer capability of a WECS with fixed speed SCIG, within a tolerable window of opportunity. Only minor modification, in the form of a global controller that will control the values of excitation capacitor as well as the tap position of the transformer, needs to be added to the existing system. It was found that annual energy production of the WECS can be improved and this improvement can be significant especially when the proposed system is implemented in a large system, which is normally the case for a fixed speed WECS.

Publications

[1] S. C. Sugiarto and S. M. Islam, "On the improvement of energy efficiency in existing fixed speed WECS," presented at the Electrical Machines and Systems (ICEMS), 2011.

[2] S. C. Sugiarto, S. Islam, and A. Abu-Siada, "Performance enhancement of grid-connected fixed speed wind energy conversion systems (WECS)," presented at the Australasian Universities Power Engineering Conference, 2009.

[3] S. C. Sugiarto, S. Islam, and A. Abu-Siada, "Power transfer capability improvement of an induction generator wind energy conversion system," presented at the TENCON, IEEE Region 10 Conference, 2009.

[4] S. C. Sugiarto and K. Tan, "Harmonics mitigation and reactive power compensation through a CC-VSI/APF WECS," presented at the Australasian Universities Power Engineering Conference, 2007.

[5] T. Archer, K. Tan, and S. C. Sugiarto, "VS-CCI and VS-CCI/APF configuration for PMSG wind energy conversion system," presented at the Australasian Universities Power Engineering Conference, 2007.

[6] A. A. Setiawan, S. C. Sugiarto, Y. Zhao, C. V. Nayar, M. E. Wijaya, E. Melfiana, *et al.*, "Development of sustainable power and water supply for remote areas and disaster response and reconstruction in Indonesia," presented at the AUPEC, 2007.

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Acronyms

DVR	Dynamic Voltage Restorer
ECS	Energy Capacitor System
FACTS	Flexible AC Transmission System
FRT	Fault Ride Through
FSC	Fixed Series Capacitors
FSIG	Fixed Speed Induction Generator
GW	Giga Watt
GWh	Giga Watt Hour
IPFC	Interline Power Flow Controller
LVRT	Low Voltage Ride Through
MWh	Mega Watt Hour
OLTC	On Line Tap Changing Transformer
SCIG	Squirrel Cage Induction Generators
SMES	Superconducting Magnetic Energy Storage
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
SSSC	Static Synchronous Series Compensator
TCR	Thyristor Controlled Reactor
TCSC	Thyristor Controlled Series Capacitor
TSC	Thyristor Switched Capacitor
TSR	Thyristor Switched Reactor
UPFC	Unified Power Flow Controller
VAR	Variable Ampere Reactive
VSWT	Variable Speed Wind Turbines
WTGs	Wind Turbine Generators
WECS	Wind Energy Conversion Systems

1. Introduction

1.1 Introduction

Wind is the world's fastest-growing energy source with an average annual growth rate of 29% over the last ten years. In 2007, global wind power generating capacity crossed 94 GW. This represents a twelve-fold increase from a decade ago, when world wind-generating capacity stood at just over 7.6 GW. Being an emerging fuel source a decade ago, wind energy has grown rapidly into a mature and booming global industry. Further, the power generation costs of wind energy have fallen by 50%, moving closer to the cost of conventional energy sources. The future prospects of the global wind industry are very encouraging and it is estimated to grow by more than 80% over the next five years to reach 600 GWs by year 2018 [1]. In Australia, wind industry has made a significant leap forward in 2013 with the completion of the Southern Hemisphere's largest wind farm, the 420MW Macarthur project in Victoria. [1] Driven by Australia's vast resource potential and supportive government policy, wind power now supply over 9,200GWh of the nation electricity each year. The Australian government sets a renewable energy target that call for at least 20% of Australia's electricity supply from renewable sources by 2020, which is equivalent more than 45,000GWh. [1] It is expected that utilities and generating companies will rely heavily toward wind farms to achieve this target.

There are many types of WECS for connecting the wind turbine generators to the electricity grid. The two major classifications are Fixed Speed and Variable Speed. The variable speed WECS employ a power electronic interface together with synchronous and asynchronous machines while the fixed speed WECS are connected directly to the grid. The power conditioning system in variable speed WECS has several advantages including reactive power support to the grid but are expensive and introduce harmonics. The fixed speed WECS employing SCIG are rugged and much less expensive. They require little maintenance and are highly reliable compared to the multi component variable speed WECS. They occupy the bulk share of the World's wind energy market. However, the SCIG-

WECS when integrated to a grid, the rotor speed allowed to vary in a very limited range and the voltage need to be maintained at the grid connection point. This project will develop an enabling technology in renewable energy conversion system that will allow an efficient cost effective way of integrating fixed speed wind turbine generators to the grid. The SCIG has terminal capacitors installed but also require some reactive power support from the grid. The capacitors typically provide the no load excitation. The optimisation of wind turbine driven induction generators has been well studied for stand-alone case but there has not been any attempt made so far to study the optimisation prospects for grid connected cases even though the scope of large energy gains are in such cases because of their large capacity. This is mainly because researchers have overlooked to take for guaranteed that the SCIG-WTGs provide no scope for speed and voltage optimisation issues as the machine is grid connected. However, when looked carefully at the characteristics of both the Wind Turbines and the SCIG it is revealed that there is a limited opportunity to vary the speed and voltage to obtain significant gain in energy output without sacrificing grid requirements. This research proposes a novel optimisation scheme for the fixed speed WECS employing the SCIGs without adding any expensive hardware. The main objectives of this research are to:

- Develop a maximum energy extraction scheme for the wind-driven grid-connected squirrel cage induction generator.
- Investigate the effect of different load models and scenarios
- Model the interaction between excitation capacitors, OLTC and different load models on the power curve of the wind turbine generator.
- Develop a supervisory control algorithm to vary the excitation capacitance and OLTC settings to maximize the power fed to the grid meanwhile keeping the terminal voltage and frequency within their permissible limits.

Wind turbine prime movers convert the wind energy into electrical power using a generator. The turbine characteristic is such that it has the best conversion efficiency at certain rotational speed corresponding to a certain wind speed and the efficiency drops either way. Operating at variable shaft speed enables a greater percent of available wind energy to be converted to electrical power that is why synchronous generator does not provide maximum power extraction from the wind energy because the prime mover has to be operated at constant speed (synchronous speed). Self-excited induction generators are a good candidate for wind powered systems operating in parallel with an existing power grid because they are simple and they do not need an external power supply to produce the excitation magnetic field. This is particularly applicable where the average wind speed is favourable and consistently available. The squirrel cage induction generator has the following advantages[2]:

a) Rotor bars have more thermal and electrical withstand limit, as a result more power can be generated with same rating of wound rotor machine.
b) It is cheap, rugged and easily available.
c) Rotor bars are less prone to failure.
d) No brush loss.
e) Lower weight and inertia.
f) It has a self-protection mechanism because the voltage collapses when there is a short circuit at its terminals.

Variable speed induction generators can be connected to the grid via a power electronic interface (AC-DC-AC converter) to allow the variation of turbine speed and to convert the variable generated voltage to fixed voltage and frequency [3, 4]. However, using a power electronic converters will incur extra cost, losses and will inject harmonics into the grid. Most power converters has a six pulse rectifier at the front end and hence introduces sizeable amount of 6k+/- 1 characteristic harmonic frequency currents in the stator windings. Furthermore, using power electronic interface usually complicates the system at the expense of reliability. Most wind energy conversion systems use fixed speed induction generators which can be connected directly to the grid to provide sinusoidal electrical power at any turbine shaft speed (above synchronous speed) but without optimisation these WECS do not run efficiently most of the time and they draw some reactive power from the grid [5]. The fixed speed machine, although with a decreasing market share, still captures about 30% of all wind power generation for its simplicity and low cost. [6, 7] Moreover, the mechanical conversion efficiency varies considerably with wind speed. The system will not be able to extract maximum energy in a higher speed range; as a consequence the output exported power to the grid will be saturated in higher wind speed range [8, 9]. An induction generator connected directly to the utility grid would allow the speed to vary in a very narrow range, and so the wind turbine operates of optimum efficiency only within a small range of wind speed variation.

An induction generator driven by wind turbine should be supplied by reactive power in order to build its voltage. This reactive power is provided either from an external excitation capacitor or directly from the utility grid [10, 11]. However the utilities are concerned on maintaining a power factor at the connection point and are not keen to supply reactive resources to the SCIG. In this research external excitation capacitor is used to provide the required no-load reactive power to the induction generator. In addition, an online tap changing transformer (which is considered as an AC-AC converter) is used to keep the terminal voltage at an acceptable limit. In all other studies, researchers have given concern to extract maximum power from the wind turbine. However, no concern has been given to the generator efficiency. This research aims to develop a novel control algorithm to maximise wind power extracted as well as maximising generator efficiency. The minimum and maximum values of capacitance required for self-excitation have been analyzed previously [9–12]. The relationship between the value of the load, capacitance, and speed has been investigated. However, no attention has been given to the influence of load type on the induction motor characteristics. In this research the relationship between speed, capacitance, and load type is determined so that the characteristics of the induction generator for self-excitation with different static load types (i.e. constant power, constant current and constant impedance) can be established. This relationship is important to find the region where the induction generator can continue to operate without loss of self-excitation. In previous studies [12-14] it is reported that the dynamically generated voltage varies with the value of the load, but there is no study shows the effect of load type on the dynamic speed of the rotor. In this research, the effect of different static load models on the rotor speed will be investigated.

The proposed control system in this research will monitor the difference between the actual and the desired generator output power, speed and voltage to adjust the external capacitance and OLTC setting so that maximum output power delivered to the grid is achieved; in the same time keeping its terminal voltage and frequency within their permissible limits. A dynamic model for the wind energy conversion system is developed for both controlled and uncontrolled operation. The model is then used to theoretically predict the changes in shaft speed, torque, and generator power in response to changes in wind speed. Preliminary results based on computer simulations are given in the next section. The proposed technique does not employ any expensive AC-DC-AC converter but exploits the existing capability of the equipment and maintains system simplicity. The model will be validated through a laboratory prototype model using a microcomputer-controlled wind turbine simulator and squirrel cage induction motor.

Due to simplicity and cost advantage, an opportunity of an existing and proposed wind farm is presented on fixed speed wind energy conversion systems employing induction machines. These direct connected machines offer converter-less operation but must be tightly controlled to synchronize voltage and frequency for grid connection. In motor technology, excitation control and speed control are well established to achieve better efficiency. This paper aims at explaining fixed speed wind generator efficiency improvement by controlling the generator terminal voltage using tandem control of excitation capacitors and OLTC transformer to match the required rotor speed of the WTG for maximum aerodynamic conversion efficiency. Results show that improvement in energy output is possible. This could translate to millions of additional MWh into the grid for medium to large turbines over their lifetime.

The need of cost effective, sustainable and efficient renewable energy system is inevitable especially with the growing world energy demand and increasing concern over the problem of global warming as well as rapid depletion of the conventional fossil fuels. Out of the renewable energy system, the wind energy conversion system is seen to be the most promising as it is a mature technology with many research efforts dedicated to improve its performance. Wind system can be classified into the fixed speed and the variable speed system, each with its own advantages and disadvantages. Although a lot of the newer wind energy conversion systems are the variable type as it can extract more power from the wind through the utilization of power electronics interface, many large WECS are fixed speed systems. There has not been much literature covering the efficiency enhancement of the fixed speed system compared to the variable speed one. This is suspected to be due to the limited improvement that can be achieved without the utilization of the power electronics converter. However, if carefully observed this small window of opportunity can translate to a substantial benefit due to, inter alia, the large size of the system as well as the minor modification that need to be implemented to the current system. Moreover, to eliminate the fixed speed systems and convert them to operate as variable speed WECS will require a substantial financial investment.

Depending on many factors such as the wind resources at the site, this becomes an optimization problem of finding the most valuable design for the least amount of investment. In some cases, the extra cost of converting the current fixed speed system configuration into a variable speed WECS cannot be justified with the extra power transfer that can be injected to the grid and hence in these cases the fixed speed wind system provide a more economically efficient solution.

1.2 The Potential of Renewable and Wind Energy

Interest in the increasing utilisation of renewable energy has been growing, largely as a reaction of increasing energy consumption worldwide, the depletion of fossil fuel and uncertainty in its increasing price as well as the increasing environmental concern in the form of global warming and greenhouse effect.

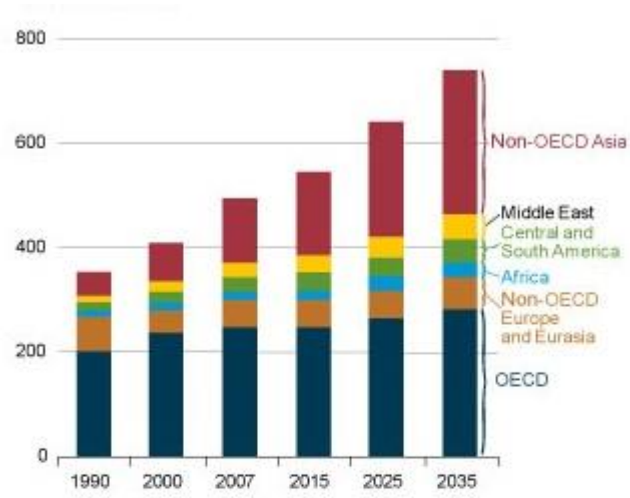


Figure 1-1 World energy consumption by region (in quadrillion Btu) [15]

The increasing trend of the world population with a predicted expansion from the 7 billion people today to nearly 9 billion people in 2040 is seen to be the inevitable fact that is a prerequisite to a global economic growth. The increase of the global energy consumption is a direct result of this expanding population growth.

Figure 1-1 shows the world energy consumption increasing strongly over the projected period rising nearly 50% in the period of 1990 to 2035 with most of the growth contributed by emerging economies outside the Organisation for Economic Cooperation and Development (OECD), especially in Asia. In particular, China and India led the energy consumption growth of the non-OECD Asia with an increase of above 100% over the projected period, whereas, the slowest growth among the non-OECD regions is in Europe and Eurasia where substantial gains in energy efficiency are achieved through the upgrade of the inefficient Soviet era capital equipment. [15]

The use of energy, from all sources, has been increasing dramatically around the world. With the domination of fossil fuel as fuel source to power generation, this causes a significant sustainability problem as the utilisation rate of fossil fuel by modern society is much higher than the capability of the earth to regenerate this type of resources. The depletion of this finite resources will eventually be inevitable. On top of this, the prediction of oil prices will remain high as well as the increasing concern about the environmental consequences of greenhouse effect, a number of national governments have device regulations and targets as incentives in support of the development of alternative energy sources. Environmental sustainability is becoming an importantly relevant issue in the last decade since the world is starting to experience tangible effect of global warning. A lot of the contributing factor of this environmental issue can be traced from the power industry with various pollutants resulting from power generation. The concept of zero carbon and carbon trading were introduced to try quantifying the sustainability of a development. To achieve zero carbon status, two strategies can be implanted: demand reduction and offset generation.

Demand reduction can further be classified into passive methods that can be easily achieved with minimum cost, such as window treatment and insulation in buildings design. In contrast, active method can be utilised to further minimise demand, such as by properly selecting building orientation, efficient heating ventilation air condition system and energy efficient system. However, regardless of the amount of demand reduction that can be achieved by these demand reduction strategies, in order to reach zero carbon status, offset generation is required because it is impossible to eliminate energy demand altogether. The renewable energy can be utilised as a source for this mitigated demand. This type of generation power by more sustainable type of resources that is non exhaustive and have less negative impact to the environment. This causes renewable energy to be the world's fastest growing source of energy. [15]

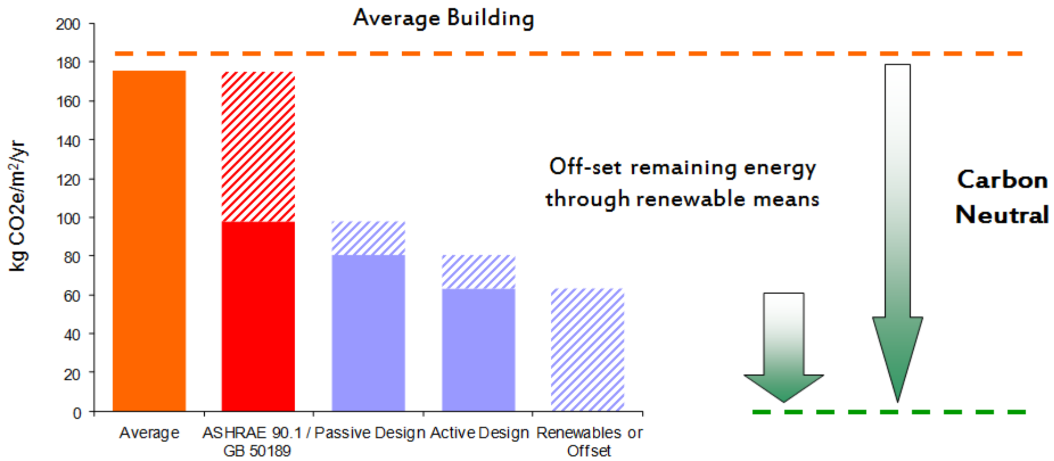


Figure 1-2 Zero Carbon Principle

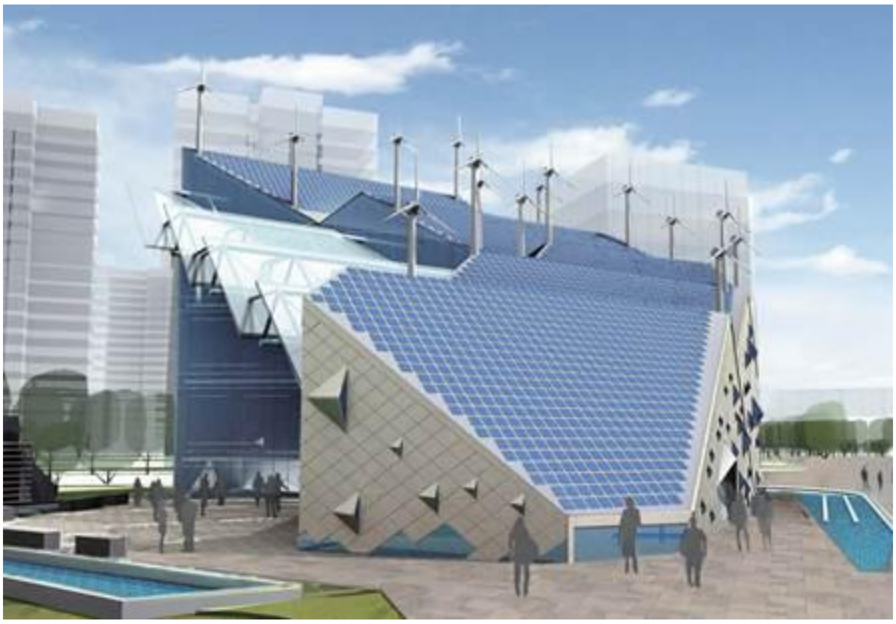


Figure 1-3 Example of Zero Carbon Building in Hong Kong

Out of the renewable energy system, the wind energy conversion system is seen to be the most promising as it is a mature technology with many research efforts dedicated to improve its performance. [16]

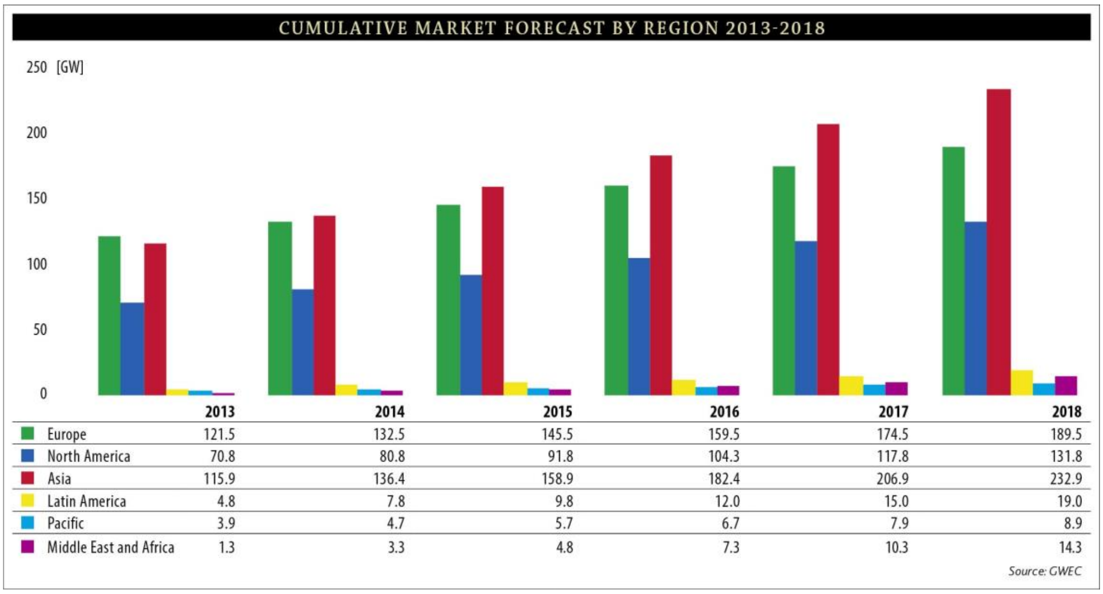
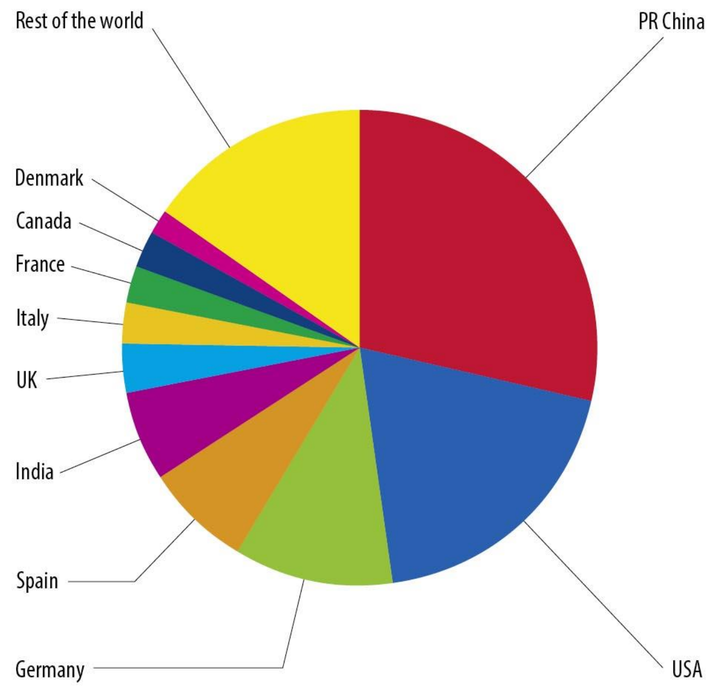


Figure 1-4 Cumulative wind energy installation in various regions in the world [1]

Figure 1-4 shows the cumulative forecast of total wind energy installation in the world. As can be seen the general increasing trend of wind energy installation is likely to continue led by the increase in the European and Asian regions driven mainly by China and India. This is further depicted in Figure 1-5 with China having the largest cumulative wind energy capacity being installed in 2013.

TOP 10 CUMULATIVE CAPACITY DEC 2013



Country	MW	% SHARE
PR China	91,412	28.7
USA	61,091	19.2
Germany	34,250	10.8
Spain	22,959	7.2
India	20,150	6.3
UK	10,531	3.3
Italy	8,552	2.7
France	8,254	2.6
Canada	7,803	2.5
Denmark	4,772	1.5
Rest of the world	48,332	15.2
Total TOP 10	**269,773**	**84.8**
World Total	**318,105**	**100.0**

Source: GWEC

Figure 1-5 Top 10 wind energy installed capacity in 2013 [1]

Increasing expectation of higher wind energy penetration into the grid is evident in the recent days, especially with the various ambitious renewable energy targets. This, among others, prompts the pressure of the exponential growth of wind turbine size, especially when they are installed on an offshore location. Other factor that contributes to this trend is cost benefit of bigger turbine power production. The development of wind turbine size and power is shown in Figure 1-6.

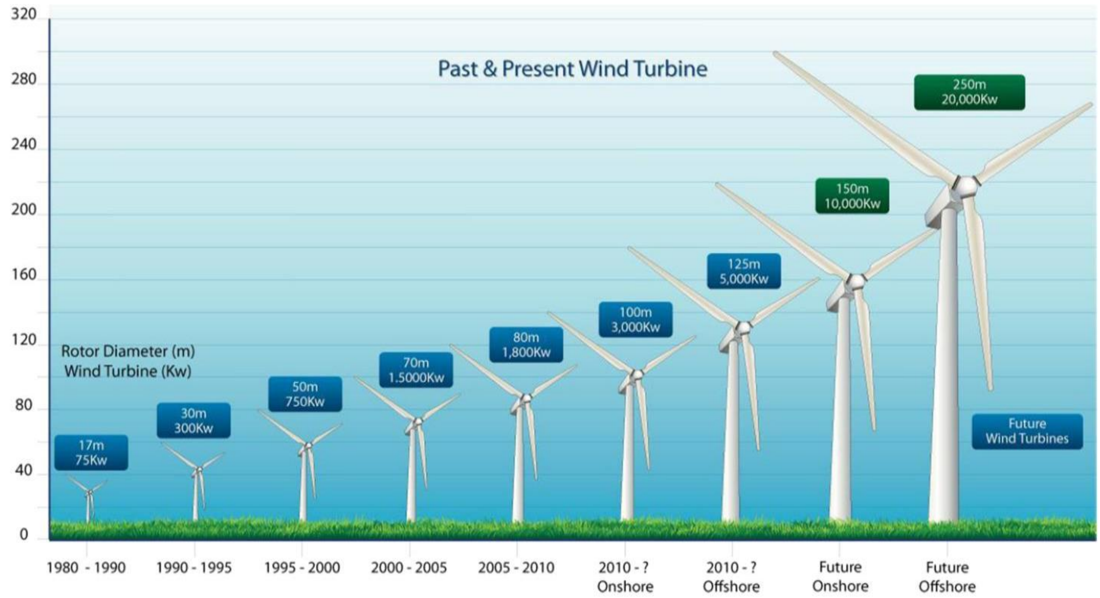


Figure 1-6 The development of power and size of wind turbine [17]

1.3 The Types of Wind Energy Conversion System

The wind energy conversion system can be classified by many aspects. From the physical point of view, wind turbine can be classified as vertical axis turbine and horizontal axis turbine.

One way in differentiating wind turbines that operate with a fixed speed to those that operate with a variable speed. In fixed speed wind system, the speed of the generator is governed mostly by the speed of the wind with little variation that can be done through manipulation of some system parameters. Whereas with variable speed wind system, a larger operating speed of the generator can be achieved through the utilisation of power electronics equipments.

Wind energy conversion system can also be classified based on the power control strategy utilised. This categorisation classifies wind system into passive stall control, active control and pitch control. All of this power control methods use the blade angle to limit the power produced by the wind turbine. In passive stall control, the blades are mounted to the nacelle at a fixed angle but they are designed so that the twist in the blades themselves will apply the brakes once the wind becomes too fast. The angle on the blades cause turbulence on the upwind side of the blade once the wind speed is above certain limit. This aerodynamic principle will cause the speed of the blades to reduce. In active stall control, the same aerodynamic principle is used to reduced the blades' speed, however, the blade pitch angle is adjustable and controlled by a controller. In pitch control, adjustable pitch angle blades are controlled by a controller to be unaligned with the incoming wind to slow the blades rotation.

Another way of describing wind system topology is by classifying the configuration into the following categories as shown in Figure 1-7.

In Table 1-1, some speed and power control combination that are not used in the wind industry today is not included. A brief explanation on each type of the wind turbine configuration is given below.

Speed control		Power control		
		Stall	Pitch	Active stall
Fixed speed	Type A	Type A0	Type A1	Type A2
Variable speed	Type B		Type B1	
	Type C		Type C1	
	Type D		Type D1	

Table 1-1 Wind Turbine Concepts [6]

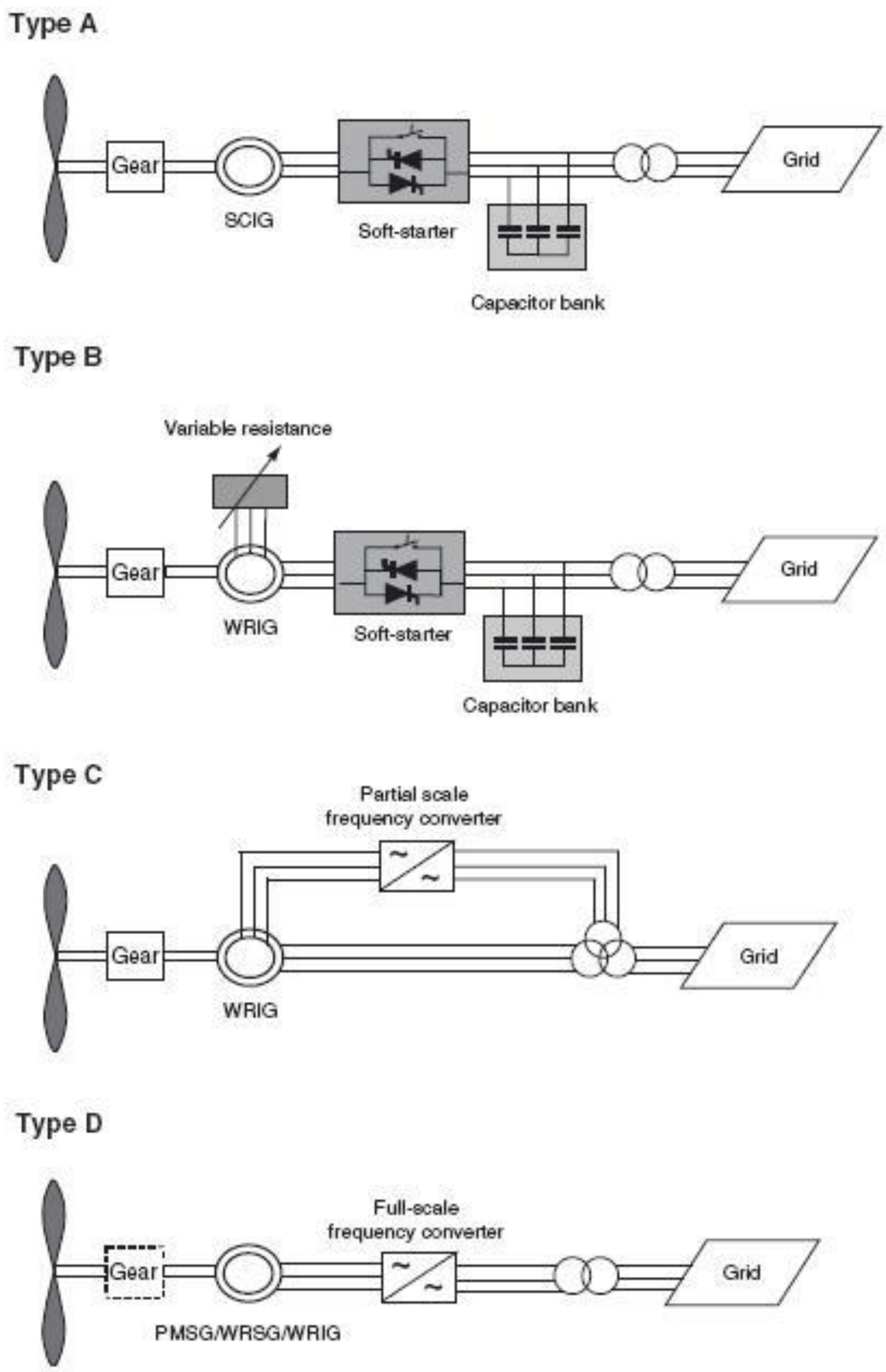


Figure 1-7 Typical wind turbine configuration [6]

1.3.1 Type A: Fixed Wind Speed

This type is used to describe wind turbine with squirrel cage induction generator directly connected to the grid without power electronics converter via a transformer. To provide reactive power support to the induction generator a capacitor bank is normally utilised. The main problem with this type of configuration is the fact that wind speed fluctuation is directly translated into power fluctuation that is injected to the grid. This can then be translated into voltage fluctuation which will worsen the problem of reactive power fluctuation that has to be provided by the grid unless there is a sufficient capacitor bank. Hence this configuration will require stiff grid and high tolerance on mechanical stress on the construction. Type A configuration can be classified into 3 types, the stall control, pitch control and active stall control. The stall control type A0 is the conventional concept around the 1980s and 1990s and had been very popular due to its low price, simplicity and robustness. In this type of turbine the stall is uncontrollable and depends solely on the input wind. The pitch control type A1 has an advantage of allowing some degree of power control by adjusting the pitch angle of the blades, however, this add to the complexity of the system and hence the cost. Moreover, the pitch mechanism is relatively slow and can only compensate slow variation in wind and not gusts. The active stall control type A2 provides a similar power quality characteristic as type A0 with better utilisation of the overall system and has recently become popular.

1.3.2 Type B: Limited Variable Speed

This configuration uses wound rotor induction generator with adjustable generator rotor resistance directly connected to the grid via a transformer. This concept is used by Vestas with their Optislip® in the mid 1990s. Both converter and passive components can be utilised to control the slip of this configuration with varying level of controllability. Generally speaking a slip up to 10% can be achieved. This concept is very rarely used and is almost non-existent in the current wind energy market. With this configuration, a capacitor bank is still needed to perform reactive power support to ensure acceptable power factor at point of common coupling.

1.3.3 Type C: Variable Speed with Partial Scale Frequency Converter

This configuration is largely known as the Doubly-fed Induction Generator (DFIG). This concept utilises wound rotor induction generator with partial scale converter connected to the generator rotor circuit before being fed to the grid. This converter provides the reactive power support and facilitates smoother grid connection. It has a wider range of slip and a cost advantage over the full scale frequency converter configuration. However, the inclusion of power electronic converter increases the complexity of the system. Moreover, issues associated with power electronic converters such as power quality and protection affected this configuration.

1.3.4 Type D: Variable Speed with Full Scale Frequency Converter

This configuration corresponds to wind energy system with generator connected to the grid through a full scale frequency converter. This converter normally includes a back to back AC-DC-AC converter. The generator can be electrically excited or excited by a permanent magnet. Gearbox can also be utilised or omitted, in which case a low speed large diameter generator must be utilised. With proper control technique this configuration can result in the best reactive power and grid connection support. However, the full scale converter can add a significant financial cost to the system. Moreover, with the additional components included in the converter, increasing maintenance and reliability issue must be taken into consideration.

Table 1-2 lists a comparative study on the different types of wind turbine configuration and it can also be seen that there is a contradiction between cost and performance from the grid perspective.

System	Type A	Type B	Type C	Type D
Variable Speed	No	No	Yes	Yes
Control Active Power	Limited	Limited	Yes	Yes
Control Resistive Power	No	No	Yes	Yes
Short Circuit (fault-active)	No	No	No/Yes	Yes
Short Circuit Power	Contribute	Contribute	Contribute	Limit
Control Bandwidth	1-10s	100ms	1ms	0.5-1ms
Standby Function	No	No	Yes +	Yes ++
Flicker (sensitive)	Yes	Yes	No	No
Softstarter Needed	Yes	Yes	No	No
Rolling Capacity on Grid	Yes, partly	Yes, partly	Yes	Yes
Reactive Compensator	Yes	Yes	No	No
Island Operation	No	No	Yes/No	Yes
Investment	++	++	+	0
Maintenance	++	++	0	+

Table 1-2 Comparison of different wind turbine configurations. [18]

Manufacturer	(%)	Concept	Diameter (m)	Power (MW)
Vestas (Denmark)	14.8	DFIG GFC PM	52 – 90 112	0.85 – 3 3
Sinovel (China)	11.1	DFIG	60-113	1.5 – 3
General Electric (US)	9.6	DFIG GFC PM DD PM	70.5 – 82.5 100 110	1.5 2.5 4.0
Goldwind (China)	9.5	DD PM	70 – 100	1.5 – 2.5
Enercon (Germany)	7.5	DD EE	33 – 126	0.3 – 7.5
Suzlon (India)	6.9	CS	52 – 88	0.6 – 2.1
Dongfang (China)	6.7	DFIG		1 – 2.5
Gamesa (Spain)	6.6	DFIG GFC PM	52-97 128	0.85 – 2 4.5
Siemens (Germany)	5.9	GFC IG DD PM	82 – 107 101	2.3 – 3.6 3
United Power (China)	4.2	DFIG	77 - 100	1.5 – 3

Figure 1-8 Top 10 Wind turbine manufacturer and their generator type and power ranges [19]

1.4 The Objectives of Thesis

The first objective of the thesis is to investigate the applicability of the concept of voltage control on the fixed speed wind energy conversion system and to model the system to understand the relationship between the terminal voltage of the generator and the active power transfer into the grid. This thesis also endeavours to investigate the utilisation of both the variable capacitor bank and the OLTC transformer to achieve this voltage control strategy.

The second objective of the thesis is to quantify the possible improvement on active power transfer of existing fixed speed induction generation based wind system by the utilization of the coordinated control strategy of the variable capacitor bank and on-line tap changer transformer. This quantification will be realized based on a comparison of annual energy production with wind data at one location with equivalent wind energy conversion system with and without the control strategy.

Wind power generation is regarded as the most promising source of all renewable energy systems to meet the global commitment to combat climate change. The recent high price of oil and increased rate of consumption of conventional energy sources has revived worldwide interest in wind turbine generators especially in favourable wind locations. Australia has many remote locations with favourable wind where the electric grid is very weak and the cost of diesel fuel is very high. However, it is now anticipated that an increased contribution to grid generation will come from both onshore and offshore wind farms. Integration of wind power with a utility grid is not straightforward because of the system requirements. In this research a concept to advance the knowledge in the possibility to improve the power transfer of the in the wind-driven grid-connected induction generator research area is presented. The results of this project will be of relevance to the wind turbine operators and manufacturers in their design and operational strategy to extract maximum power from a wind driven induction generator as it explains an optimisation scheme to change the excitation capacitance and the OLTC setting in sympathy with the available wind power. Figure 1-9 shows the stator line voltage of an SCIG with various levels of terminal excitations as a function of the rotor speed.

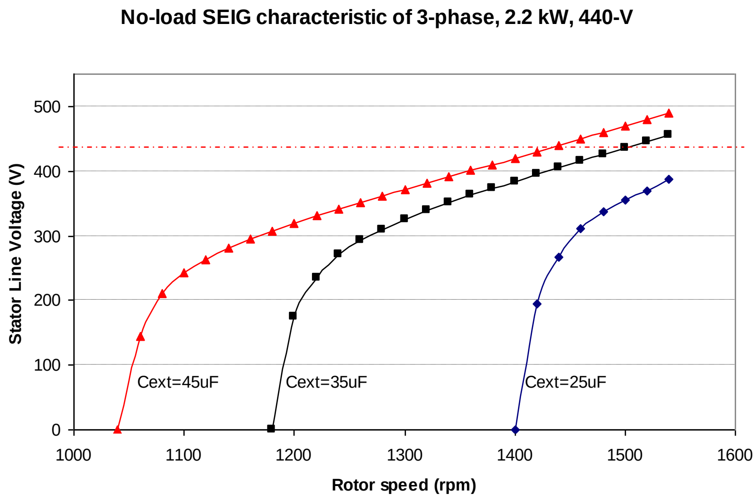


Figure 1-9 Stator Voltage versus Rotor Speed

Figure 1-10 shows the variation of electric torque of a SCIG as a function of generator speed at various terminal volts. Even though our grid is designed for a fixed voltage and fixed frequency, the regulating standards allow for small variations (i.e. up to 5 % slip for the SCIG and ±10% voltage regulation). An increased slip will incur minor additional rotor losses but the gain in energy output as shown in Figure 1-9 and Figure 1-10 will be significant.

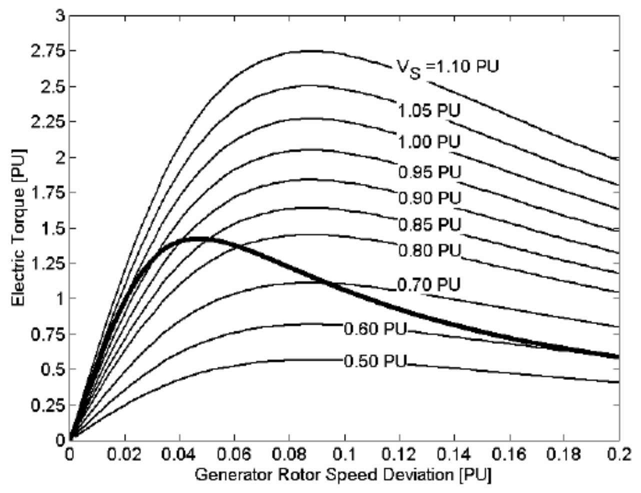


Figure 1-10 Generator torque versus rotor speed [20]

At this stage no such technique exists worldwide that apply to a fixed speed WECS. The proposed system endeavour to increase power extracted from the WTG and yet is simple as it does not call for any power electronic converter to connect the induction generator to the grid.

1.5 The Outline of Thesis

This thesis is broken up into several chapters. This first introductory chapter covers the background of the potential of renewable and wind energy and the types of wind energy conversion system. The objective and contribution of this thesis is also elaborated in this chapter.

Chapter 2 gives a more detailed narrative on the challenges of increasing the penetration of wind energy into the current power system especially for the directly connected SCIG fixed speed wind energy conversion system.

In chapter 3 the components of the wind energy conversion system are explained starting from the characteristic of the wind, the wind turbine theory, induction generator theory, reactive power compensation requirement and the relationship between the terminal voltage of the induction generator, the reactive power consumption and the active power produced.

In chapter 4, test system data will be evaluated for model verification.

In chapter 5, a simulation model was built on the Matlab Simulink® software platform. Each block of the model is explained. This model was then compared to data from real wind turbine to ensure reasonable selection of machine parameters was utilised.

Chapter 6 describes the simulation modelling that was performed to illustrate and substantiate the principle of this thesis. The simulation model is used to simulate some scenarios including variability in wind input and control parameter selection.

Chapter 7 will provide a conclusion to this thesis with future direction suggested.

2. Background

2.1 The Proposed System

The system proposed in this paper is a fixed speed WECS directly connected to the grid without the utilization of power electronics converter. SCIG is utilized and mechanically coupled to the shaft of the wind turbine through a gearbox. This proposed solution also includes a variable capacitor bank and OLTC transformer. The grid governs a fixed speed fixed frequency operating point of the system and the SCIG can only run with a limited rotor speed variation, which is governed by the slip. However, unlike the conventional system where the SCIG terminal voltage depends solely on the grid voltage and wind speed without any control mechanism, in this proposed system some control can be exerted through the utilization of the OLTC transformer supported by the variable capacitor. This configuration results in the possibility of extending the operating range of the SCIG in terms of terminal voltage and rotor speed compared to the conventional system. The variable capacitors and OLTC transformer will be controlled through a supervisory control system. The tandem use of OLTC transformer and variable capacitor is necessary as, although the main objective is to increase the power transfer capability of the system by selecting the optimum operating voltage of the SCIG, the power factor at the point of common coupling has to be maintained close to unity and the voltage at the grid side has to be kept within an acceptable range as specified by the grid code. The power transfer improvement is intended to be effective regardless of the existence of under-voltage of overvoltage in the grid voltage. In contrast with the conventional system where changes in the grid voltage translates directly into variations in terminal voltage of the SCIG, in the proposed system, the terminal voltage will be kept at a level where the power transfer is maximized within the limitation of the tap position of the OLTC transformer. The compensation proposed is steady-state compensation in contrast to a transient one. A threshold will be designed before the supervisory control system takes places to avoid excessive switching of the transformer taps and capacitors. This will reduce the wear and tear of these equipments and maintain the equipments within their intended lifespan. Due to this limitation, the proposed system is not intended to compensate wind gust and other wind event that are characterized by a sudden temporary change in wind speed. In contrast, it is targeted to be effective in capturing the potential energy transfer improvement due to diurnal and seasonal wind condition.

2.2 Challenges in the Wind System

The utilisation of WECS as energy source, like any other energy sources, is not without its own issue. The intermittent nature of wind causes energy generation to be fluctuative, which directly translate to fluctuation in voltage and active power flow. Furthermore, the reactive power flow, as a result of the utilisation of induction generator as well as power electronics, is problematic to the stability of the power system, with its impact dependent on the degree of preparation. Although these problems will create issue for stand-alone system, especially if connected to sensitive load, they are really relevant in grid connected system. Grid integration problems have hampered the increasing penetration of WECS. Traditionally, the power system was designed to cater for a centralised conventional generator with controllable power generation. The energy generated from these generators can be easily planned and controlled by increasing/decreasing the fuel, generally coal or oil for base load power plants with gas becoming more and more popular as peaking plants.

With the increasing penetration of renewable energy, especially wind energy, where generation cannot be planned, the power system faces certain issues in maintaining its power quality and stability. Grid management becomes gradually more complex with the advent of renewable power generation which inevitably cause utility companies to face a number of challenges in grid planning and operations where reliability is the top priority. [21] The extend on how much disruption can be tolerated by the grid due to the inclusion of wind energy in the fuel mix or how much support must the wind energy system provides for the grid is governed by the grid code. The requirements demanded by grid code varies from countries to countries and regions to regions.

To mitigate issues relating to wind energy integration, three factors are deemed to be essential prerequisites: availability of resources, adequacy of technology and infrastructures and readiness of governance in the form of grid code and standards.

2.3 Wind Availability

The integration of wind energy as resources into the grid fundamentally change network planning objectives, as utilities are required to take into account the intermittent nature of wind availability. Although, due to the movement of air, wind resource always exists, a minimum cut in wind speed is required for wind turbine to be operational. Wind farms, as any other renewable energy power plants, are highly reliant on the weather conditions and locations. Area with ample wind resources are generally remote and might be far from load centre and grid infrastructure. Due to the variable nature of wind resources, optimal sitting of wind turbine, for which knowledge of specific wind resources analysis, such as availability, magnitude and variability, is essential to optimise the wind energy that can be harness. An example of wind resources map is shown in Figure 2-1, which is an important and very useful to determine the suitability of wind energy as fuel source. In some regions, this information is readily available, whereas in many developing countries, such as those in the Asian region, there is limited understanding of location and potential wind energy source characteristics. A wind energy resources map would allow planners to match potential wind energy sources with that of load centres. This can also help to determine and identify the transmission capacity required and lack thereof to move the energy created from the wind to be consumed to the load centre. This might call for the need of long term grid planning to optimise the configuration of the grid with respect to the availability of the wind energy.

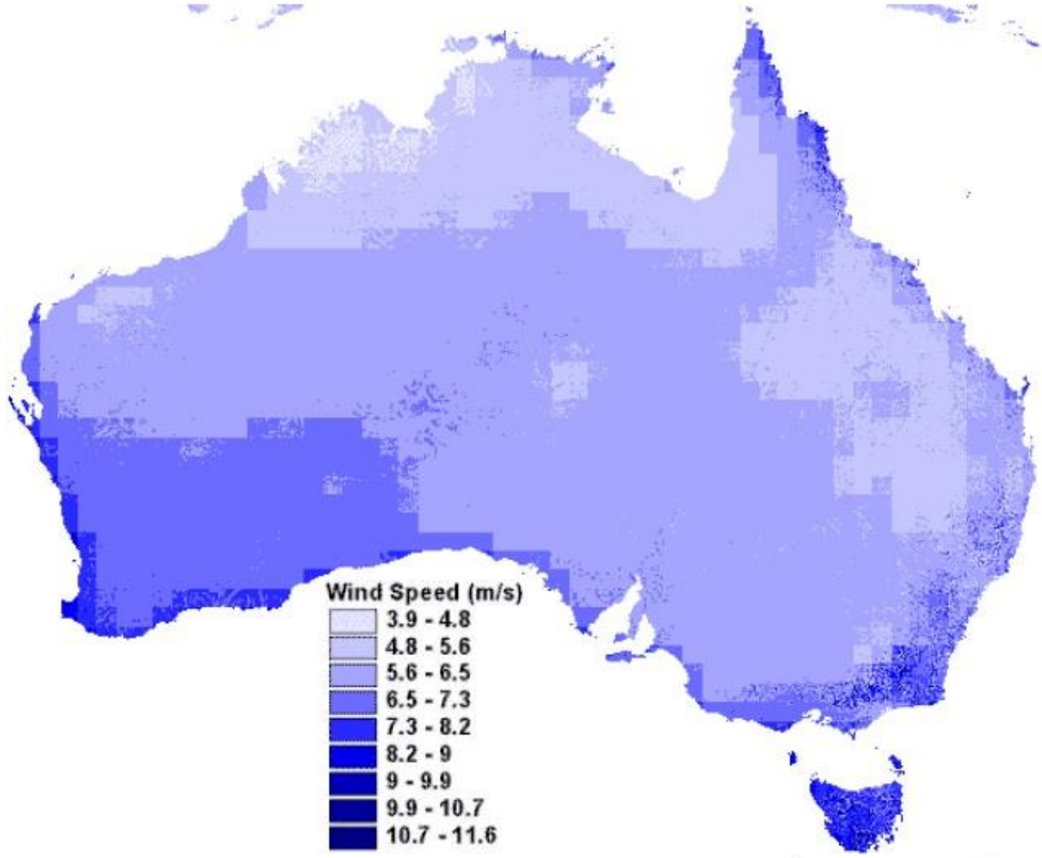


Figure 2-1 An Example of wind speed for the period of May 1997 – April 1999 [22]

2.4 Technological and Infrastructure Requirement

To realistically realise the potential of wind energy, it is essential for its development to be accompanied by the advancement and adoption of technology and infrastructure requirement. This aspect could be broken down into the availability of competent labour, the proximity of wind energy source to the electricity grid with transmission network that is capable to cope with the extra generation capacity at intermittent time and the availability of equipment to efficiently convert wind energy into electricity while maintaining the required grid integrity and stability. Technical expertise of skilled labour is necessary to operate and maintain the equipment and optimise the operation and maintenance of the WECS. It is, therefore, essential that competence building be part of the prerequisite for the increasing penetration of wind energy into the current power system. The second barrier to increasing penetration of wind energy to the current grid is the proximity of the source to transmission network. Electricity networks are generally established along narrow corridors and are often situated far away from wind sites. The long distance increases connection cost as utility need to upgrade and extend the network to the new wind energy sites. Other factors that might create issue in the integration of wind energy from infrastructure point of view including the capability of existing equipment in the power system to accommodate not only the increasing generation and hence capacity of the grid but also the fact that these new generation might be decentralized and intermittent.

The extend to all these issues depends greatly on the level of penetration of wind into the power grid as most legacy power systems were not design to accommodate high penetration level of renewable energy including wind energy. It is important to ensure that grid integrity and stability are not compromised but the inclusion of wind energy into the power system. Some new regulation even mandated that renewable energy generation including wind must have positive impact to grid stability and integrity.

2.5 Codes and Regulatory Framework

Adequate wind resource, sufficiently advance knowledge, technology and infrastructure are not enough to promote higher penetration of wind into the current fuel mix of the power industry. Formal standard, codes and regulatory framework are absolutely essential to control and mitigate negative impacts that may result from unregulated connections. In contrast to conventional fossil fuel power generation, renewable energy including wind energy are intermittent, which might expose the power system to new risks. In the modern society, the reliability and stability of the grid is given high priority and hence the need for adequate codes and connection guidelines for wind energy to help improve not only the stability and reliability of the network but also the quality of supply is unavoidable and should focus on achieving smooth integration of wind energy into the current grid. The degree of strictness in the different categories governing the wind connection into the grid differs from countries to countries and regions to regions. This might be depending on many factors including the current state of gird reliability, the degree of penetration of renewable energy in the power system, the technology and skill level of renewable energy equipment and infrastructure as well as government policy and plan regarding the utilization of renewable energy as fuel in that particular country or region.

2.6 Challenges in the Chosen System

Currently, the most popular wind turbine configuration seems to be the variable speed with pitch control. However, still some manufacturers are providing the conventional stall and active stall fixed speed wind turbine especially for countries where the grid codes do not demand reactive power control, such as in China, India and part of the US. [18]

Constant speed turbine utilises squirrel cage induction generator directly connected to the grid via a transformer. Due to its simplicity, this configuration is seen to be the most robust and cost effective. It is a simple system with few components and hence is a generally more reliable system and requires less maintenance, other than on the gearbox. However, this type of configuration has many deficiencies and aspects that have to be considered as listed below.

2.6.1 Reactive power regulation

Without the power electronic converter, a fixed speed system does not have a decoupled active and reactive power control. Due to this reason the reactive power consumption depends on the active power produced, which in turns depends on the wind speed input. In some circumstances, reactive power requirement of the wind energy system is obtained from the grid. When this happen, it is important that there is a limit of how much reactive power will be supplied to the system before it gets disconnected from the grid to prevent other grid issues.

In modern power system, it is preferable for wind energy conversion system to not rely on grid for reactive power supply but instead utilise capacitor bank or other components such as SVC and STATCOM. Reactive power support can be categorised as shunt or series compensation.

Shunt compensation can be further classified into the following main categories.

1. Shunt Capacitor

Shunt capacitor is the cheapest reactive power compensation. It is simple and inexpensive to maintain. Shunt capacitors can be in the form of fixed capacitor bank connected at the induction generator terminal at all time or multiple capacitor banks that are mechanically switched in according to need. [23] The mechanically switched capacitor has a low smoothness of control, as it is dependant solely on the number of capacitor switching units used. [23] Moreover, the mechanical switches and relays have the disadvantage of being unreliable and requiring high maintenance. [23] The main problem of this type of VAR support is the inability of the capacitor banks to deliver high reactive power when the voltage is low as the reactive power supplied is directly proportional to the terminal voltage of the induction generator. Hence, during low voltage condition, the reactive power supplied to the system drops, which in turn will further compound the problem.

2. Synchronous Condenser

Synchronous condenser can be made of a newly built condenser or utilises older synchronous machine to provide reactive power control while avoiding new investment cost. [24] With the inclusion of a thyristor controlled excitation system, the response time of the machine is improved compared to the older static excitation system. [24] Synchronous condensers are rarely used today as they require substantial foundations and significant amount of starting and protective equipments. [23]

3. Thyristorised VAR Compensator

Thyristorised VAR compensator is capable of achieving fine control over the entire VAR range with faster response time compared to the synchronous condenser. [23] This compensator, which can also be called the Static VAR Compensators (SVC) can be grouped into two basic categories as listed below.

- Thyristor Switched Capacitor (TSC)
- Thyristor Controlled Reactor (TCR)

It is also common for the TSC and TCR to be combined, which are generally referred to as the static VAR compensator (SVC). SVC has many configuration, some of the more popular consist of fixed capacitor in series with Thyristor Controlled Reactor (TCR) or Thyristor Switched Capacitor (TSR) in series with TCR. Another can be built up with a Thyristor Switched Capacitor (TSC) in parallel with a Thyristor Controlled Reactor (TCR) supported with a shunt fixed capacitor.

4. Saturable Reactors/Inductors

Saturable reactors or inductors can also be used to provide static reactive power compensation. This inductor is typically connected in series with a slope correcting capacitor and both are paralleled with a shunt capacitor to provide the capacitive voltage.

5. Voltage Source Converter

STATCOM is a Voltage Source Converter (VSC) based device that is capable of compensating the active and reactive power need of the system. The reactive power output of a STATCOM is not affected by the terminal voltage level of the induction generator. STATCOM significantly increase the complexity of the system. VSC, in its first application was implemented with Gate Turn-off Thyristor (GTO) and nowadays utilises Insulated Gate Bipolar Transistor (IGBT). VSC for STATCOM can also be in the form of a multilevel converter.

6. Superconducting Magnetic Energy

Superconducting Magnetic Energy Storage (SMES) is a device for storing and instantaneously discharging large quantity of power

Series compensation can be classified into the following categories.

- Fixed series capacitors (FSC), which can be inserted as one block or through a series of sub-blocks
- Thyristor Controlled Series Capacitor (TCSC), generally consists of a TCR in parallel with a FSC
- Static Synchronous Series Compensator (SSSC) is made up of a VSC and acts as a controllable series capacitor
- Dynamic Voltage Restorer (DVR) acts independently of the source voltage fluctuation by utilising a VSC to generate active and reactive power
- Unified Power Flow Controller (UPFC) utilises two VSC back to back with a common DC link
- Interline Power Flow Controller (IPFC) links two VSC from two different power lines through a common DC link
- Superconducting Magnetic Energy Storage (SMES) is a device for storing and instantaneously discharging large quantity of power

2.6.2 Power Production Fluctuation

In fixed speed wind turbine configuration, the variation in the wind speed is translated directly to mechanical torque fluctuation. This results in the fluctuation of the power that is injected to the grid, which is only slightly mitigated by the varying slip.

2.6.3 Voltage Ride Through Capability

In many modern grid codes, especially where wind penetration into the grid is becoming significant, the demand that wind turbine stay connected where there is a dip in the grid voltage for a specified period of time is included. This demand is generally cannot be met by the Type A fixed speed wind turbine.

Previously, when the contribution of wind energy into the power system is limited, wind turbine can be simply disconnected when there is a fault at the grid and then reconnected when this fault is cleared. However, as the penetration of wind into the grid is increasing significantly, it is a requirement in some grid codes for wind turbine to stay connected during some disturbances. Moreover, the wind system must also provide active and reactive power support to help the grid gain its pre-fault state with frequency and voltage recovery after the fault is cleared. Generally, reactive current should be injected to the grid during the fault to help grid recovery. After the fault is cleared, active power production should resume.

As most grid fault is detected through the large fault current, constant speed wind turbine can help in this detection. It is able to stay connected during most faults as its can handle over-current for a short period of time. However, providing reactive power support for voltage recovery after the fault is not possible as this system is completely passive. Furthermore, it draws reactive power and can put further pressure on the grid recovery after a fault.

With the increasing penetration of wind power into the current power system, more and more stringent grid code requirements are demanded to be complied by wind farms. [25-27]

Requirements such as FRT capability, reactive power support and frequency support need to be complied to a certain extent which differ from countries to countries, with some grid operator demanding more stringent requirement compliances.

The capability of the Type A system to comply with the grid code requirement is limited due to its simple construction. At the occurrence of fault, the Type A system rotor accelerates, which result in an increase in the reactive power absorption that will exacerbate the voltage sag condition.

The proposed tandem control is believed to be able to assist with marginal improvement of this LVRT capability of a fixed speed system. This will be explored as part of further research to this study. In [25], methods such as the utilisation of FACTS devices, fast pitching of turbine blades, dynamic braking resistors and SMES have been identified to be effective solutions to improve the LVRT capability.

The operating point of induction machine in the FSIG based WECS occurs only within a small window and is less flexible when compared to the variable speed WECS. To provide reactive support to the grid and satisfy grid code requirement, compensating devices such as switchable capacitor banks must be installed in the vicinity of the wind farm. Although the fixed speed system might have negative impact on the grid in terms of its LVRT and reactive power support capability in times of fault, there is a consensus that fixed speed WECS have inherent inertia response that counteract the network frequency deviation and in turn contributes to the primary frequency support. [25-27]

2.6.4 Reliability

The reliability of wind turbine can be quantified through its failure rate. With more and more turbine being installed offshore and in remote location, mitigating maintenance is one aspect that have to be considered. Components such as electrical system and its control have generally high failure rate. However, the time it takes to repair them is generally low. This is in contrast with components such as the gearbox and drive train, which have a low failure rate but high hours lost per failure. It is apparently difficult to fix gearbox. This can be seen in Figure 2-2. A detailed comparison of the reliability of direct-drive and geared wind turbines did not prove one to be more reliable than the other. [28]

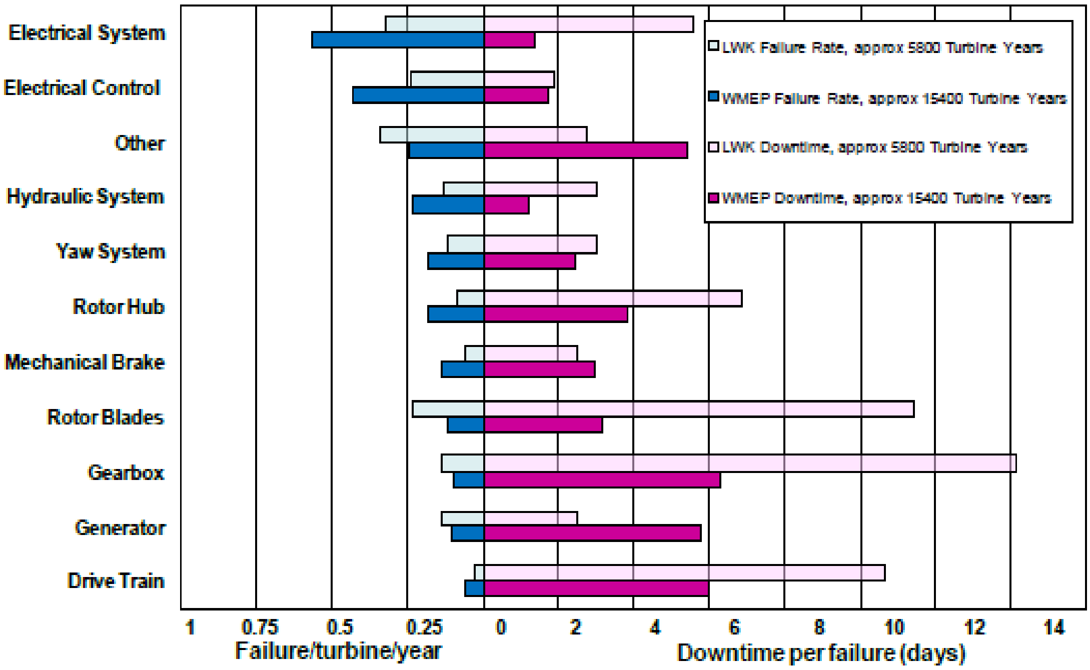


Figure 2-2 Downtime and failure rate for wind turbine subassemblies [29]

2.6.5 Active Power Regulation

From a grid operator perspective, it is important that the balance between energy demand and supply is maintained. Unlike conventional power plant, the wind is uncontrollable. Due to this reason planning active power production can only be done with the limitation of the available wind at a particular time. In other words, unlike conventional generator where fuel can be added to increase power production to satisfy demand, wind energy conversion system depends solely on the wind resource. Moreover, in a wind energy conversion system, it is important for mechanical power to be controlled and limited when the wind speed is high. This is especially important as power in the wind is proportional to a cube of the wind speed and hence a small increase in wind speed above the rated limit translates to a significant increase in the power. This power control can be done through techniques such as

- Stall control, where the blade position is fixed but stall of the wind occurs along the blade at high wind speed

- Active stall control, where the blade angle can be adjusted to create stall at high wind speed
- Pitch control, where the blade angle can be adjusted to turn out of the win

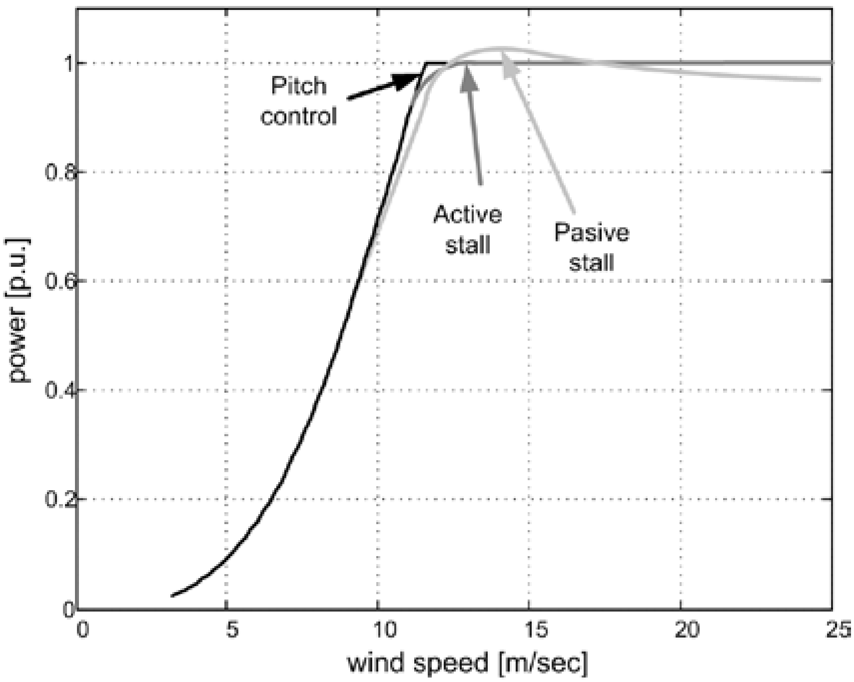


Figure 2-3 Power characteristic from different power control strategy with passive stall technique based on fixed speed machine [18]

Although the main purpose of the power control strategy is to limit power from the wind when the wind speed is high, pitch can also be utilised to maximise power when the wind is below the rated wind speed. Pitch control can also be used to help support many grid issues such as power smoothing and LVRT. [30]

2.6.6 Power Quality

As a result of the inclusion of power generator and power electronic converter in the wind energy conversion system, some harmonics and flicker might pollute and reduce power quality of the grid. For the issue of power quality IEC 610003 must be adhered to by the wind turbine. [31] The fixed speed wind generation system does not utilised power electronic converter and hence does not produce harmonics. However, voltage flicker that result from the fluctuation of the input wind can create an issue for the grid.

- Voltage regulation
- Mechanical stress especially during wind gusts
- Limited power quality control
- Power factor regulation
- Frequency regulation

2.7 Fault Ride through of Fixed Speed System

Fixed speed system wind turbine has high sensitivity to voltage sags due to the fact that the generator is directly connected to the main grid. In the case of a voltage drop, the electromagnetic torque of the generator reduces significantly while mechanical torque is still applied. This leads to the unbalance torque, which in turn leads to accelerating rotor that might lead to rotor instability. Furthermore, when a fault occurs, the induction generator will consume more reactive power to recover their air gap flux. This adds to the burden of the grid that is trying to recover from the fault. This might lead to voltage reducing further and induction generator becoming unstable requiring disconnection from the power system. Solutions to support fault ride through can be classified into 2 categories.

The first category is preventing an over speeding phenomenon by reducing the mechanical power input or consuming this power to help balance the input and output power. This can be done through pitch angle control, where the pitch angle of the turbine is adjusted so that the mechanical power input to the system is reduced. This will in turn reduce the acceleration of the rotor speed. However, this approach is limited due to the physical limitation of the blades and the pitch regulation mechanism. Another approach that can be utilised to reduce the imbalance of power at time of fault is the series dynamic braking resistor that is capable of consuming the excess power of the wind turbine and prevent the over speed problem.

The second category of recovery support of fixed speed wind turbine is by providing reactive power and hence voltage support to the generator. Several solutions have been proposed including the static synchronous compensator (STATCOM), static VAR compensator (SVC) and dynamic voltage restorer (DVR). Other components such as energy capacitor system (ECS) and superconducting magnetic energy storage (SMES) have also been reported to be able to provide the necessary recovery support for the system. In recent years, using reactive power and voltage support from nearby variable speed wind turbines (VSWT) has also been proposed and considered as promising solution to enhance the fault ride through (FRT) capability of the fixed speed system. In [32], it can be seen that the STATCOM can be utilised to perform a successful fault ride through on a fixed speed system. Because of the STATCOM operation, after the fault is cleared the terminal voltage can be recovered and the wind turbine restores its normal operation.

- Hexagram converter based STATCOM [33]
- Braking resistor [34]

In [35], it can be seen that the inclusion of tap capacitor and its proper controlled can be utilised to support the grid to recover from fault. Capacitor bank may cost effectively improve the dynamic performance of induction generator [35] and help the grid to return to its pre-fault state. As reactive power compensation equipment, the capacitor bank could also support the voltage and torque recovery, performing similar function as the STATCOM and DVR. From [35], it can be seen that the capacitor bank is able to increase the electromagnetic torque and consequently extend the stability range of the induction generator. When more capacitors are switched in after the fault occurrence, the generator speed and torque can be restored and the generator is returned to its pre fault state.

3. The Components for the Proposed System

3.1 Variability of the Wind

Wind is a clean and free energy source. However, modelling wind as an energy source is significantly different to conventional energy source due to its intermittent nature. To understand wind energy conversion system, it is important that the characteristic of wind as an energy source is explained. Air masses moves because of the different thermal conditions of these masses. The movement of these air masses is the basic physics of the existence of wind. Wind variability can be explained in both global and regional scale. On the global scale, wind is affected by both climate differences between continents on earth as well as their solar exposure. On a regional scale, wind is affected by the aerographic condition, which describes the surface structure and terrain of the region such as the ratio of land and sea as well as the number of mountains and plains. The boundary layer that is wind energy closest to the ground is the one utilized by the wind turbine to drive the turbine blades. This wind energy is turbulent owing to the roughness of the earth surface. [6]

The wind speed varies continuously as a function of height and time. The wind in the planetary boundary layers is influenced by the surface roughness and in turn this wind influence the layer above them changing the mean wind speed with height until the shear forces are reduced to zero. [36] At that height, called the gradient height, the wind speed depends solely on the pressure field and its latitude position. The rate of change of wind speed with height is called the wind shear with profile as shown in Figure 3-1.

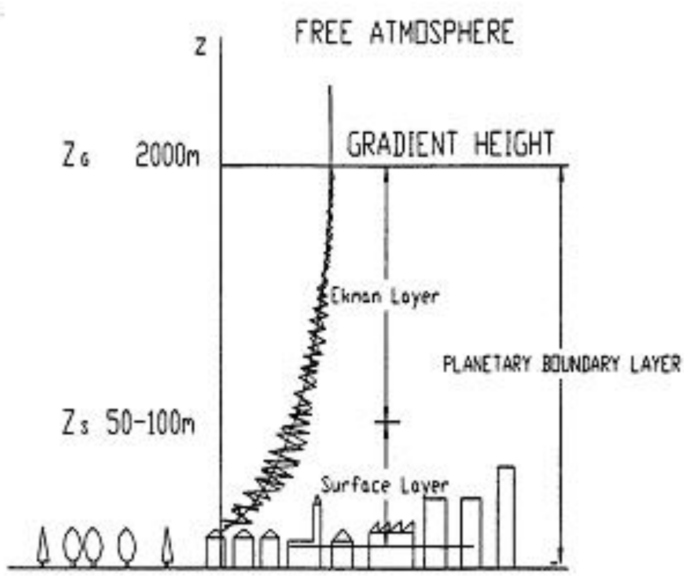


Figure 3-1 Wind shear profile [37]

A simple analytical formulation can be utilized to approximate wind speed at an elevated site. This is stated in (3-1). [36]

$$\frac{U}{U_r} = \frac{\text{In}\left(\frac{z}{z_0}\right)}{\text{In}\left(\frac{z_r}{z_0}\right)}$$

(3-1)

Where U is the mean wind speed at an elevated height z, U_r is the mean wind speed at reference height z_r and z_0 is the roughness height.

This equation can be further simplified to the commonly used form using the shear exponent α as stated in (3-2). [36]

$$\frac{U}{U_r} = \left(\frac{z}{z_r}\right)^{\propto}$$

(3-2)

Both z_o and α are site-specific parameters.

The time scales of typical wind speed variations are presented in Figure 3-2 as a wind frequency spectrum. [6, 36, 38]

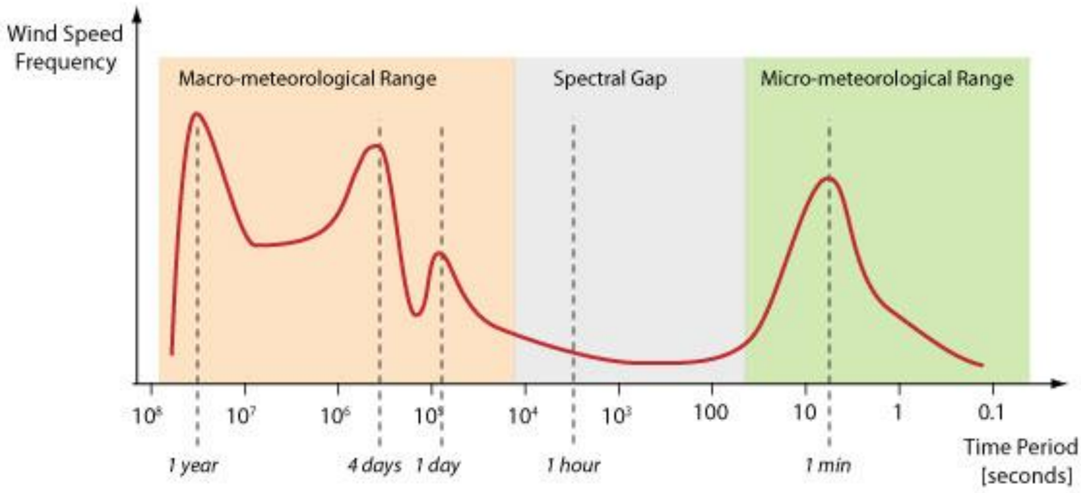


Figure 3-2 Wind speed spectrum [38]

The macro-meteorological range describes the large-scale movement of air masses and 3 peaks can generally be found in the time period larger than 2 hours.

1. The diurnal peak depends on the daily wind speed variation such as those that is caused by the land-sea breeze and the different temperature between day and night
2. The synoptic peak usually occurs with period of around 4 days and depends on the changing weather patterns
3. The annual peak varies with the degree of latitude and diminishes at locations closer to the equator. Based on Ackermann [6], it has been estimated that the variation of wind resource over the lifetime of a wind turbine (20 years) is not large and this uncertainty is much less than the availability of water for hydropower production

From the perspective of wind generation, the variation of wind speed in the macro-meteorological range mainly affect the long term balancing of the power system. [6] In the micro-meteorological range, the turbulent peak is caused mainly by gusts in the sub-second to minute range due to atmospheric turbulence.

These are caused by the mechanical mixing of the lower layers of the atmosphere by the surface roughness and have their energy centred around periods of 1 minute. [36] From the power system perspective, the turbulent peak may affect the power quality of wind power production especially for strongly grid-coupled turbine. [6] An interesting phenomenon is the spectral gap, which occurs between the period of 10 minutes and 2 hours. If an averaging period for mean wind speed is chosen to lie within this spectral gap it is possible to separate the turbulent peaks from the macro-meteorological variation. [36]

Wind is generally defined by the wind speed and direction of flow. For simplification purposes, the wind model can be defined only by its speed. [39] Wind speed for wind modelling purposes can be characterised by four components, namely, the average value component, the ramp component, the gust component and the turbulence component. [6, 39-41] This leads to (3-3).

$$U_w(t) = U_{w_{mean}} + U_{w\_ramp}(t) + U_{w\_gust}(t) + U_{w_{turbulence}}(t) \tag{3-3}$$

The wind fluctuation can be modelled by the spectral power density or actual wind measurement with instrument such as the anemometer.

3.1.1 Target Wind Speed

For each wind turbine, it is possible that the gearbox ratio is adjusted so that the induction machine is running at a speed that corresponds to the optimal tip speed ratio to operate at the optimal Cp point. As the tip speed ratio is dependent on wind speed, it is beneficial to match the average wind speed at a wind farm location to the target wind speed of the SCIG to improve the power production of the WECS.

3.2 Wind Turbine Theory

3.2.1 Wind turbine power and cp lambda curve

The power of an air mass with an air stream speed U_w through an area A with air density ρ is based on cube law equation. This equation denotes the total power in the wind as stated in (3-4).

$$P_w = \frac{1}{2} \cdot \rho \cdot A \cdot {U_w}^3 \tag{3-4}$$

The air density ρ is a function of air pressure and air temperature. The air density as a function of altitude above sea level z, can be defined as shown in (3-5).

$$\rho(z) = \frac{P_0}{RT} \cdot \exp\left(\frac{-gz}{RT}\right) \tag{3-5}$$

where P_0 is the standard sea level atmospheric density ($1.225 kgm^{-3}$), R is the gas constant for air ($287.05 Jkg^{-1}K^{-1}$), g is gravity constant ($9.81 ms^{-2}$) and T is temperature in Kelvin. [6]

However, naturally, the wind turbine electrical power output is less than this power and is limited by the power coefficient Cp. It is impossible for the wind turbine to extract the total power in the wind, as this will cause the air mass to stop completely in the rotor area. This is the result of the reduction in air mass speed when the original power in the air mass is converted into the mechanical energy that rotates the turbine rotor. Hence, the power developed by the wind turbine is given by the (3-6).

$$P_t = \frac{1}{2} \cdot \rho \cdot A \cdot {U_w}^3 \cdot C_p \tag{3-6}$$

A German aerodynamicist, Betz, conducted a detailed analysis of wind turbine performance and found that the maximum value of the power coefficient is $\frac{16}{27}$ or around 0.593. [39] This is eventually called the Betz limit of wind turbine *Cp*. Practical wind turbines designed for power generation generally have *Cp* values below 0.45.

The power coefficient is a function of turbine's blade tip speed ratio λ and the turbine's blade pitch angle β. However, since most of constant speed wind turbine is equipped with stall control instead of pitch control, the *cp* is just a function of λ and β can be left out of the equation. The wind turbine rotor can be approximated through a general equation as shown in (3-7). [42]

$$C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{-c_5/\lambda_i} + c_6\lambda$$

(3-7)

Where,

$$\frac{1}{\lambda_1} = \frac{1}{\lambda + 0.08\beta} + \frac{c_0}{\beta^3 + 1}$$

(3-8)

With λ being defined by

$$\lambda = \frac{U_T}{U_w} = \frac{\omega_r R}{U_w}$$

(3-9)

where U_T is the turbine's blade tip speed, ω_r is the rotor rotational speed and R is the radius of the blade.

The power coefficient relationship with tip speed ratio varies slightly depending on the size, type and operating condition of the wind turbine. From the Cp-λ curve characteristics, it is possible to generate the relationship between the wind turbine output power and wind turbine shaft speed at various given wind speeds.

3.2.2 System inertia

The energy stored in a rotating mass such as an induction machine can be defined by (3-10).

$$E = \frac{1}{2} \cdot J \cdot {\omega_m}^2$$

(3-10)

where J is the inertia of the machine and ω_m is the rotational speed of the machine. The inertia constant H can also be used to quantify inertia by giving the indication of the time that the generator can provide nominal power by only using the energy stored in its rotating mass. The inertia constant uses S to specify the nominal apparent power of the generator and is defined in ((3-11).

$$H = \frac{J \cdot {\omega_m}^2}{2 \cdot S}$$

(3-11)

Typical inertia constant for the generators of the large conventional power plants are in the range of 2-9s. [43]

The inertia of a body can be expressed as

$$J = \sum m_i \cdot {r_i}^2$$

(3-12)

where r_i is the radial distance from the inertia axis to the representative particle of mass m_i and the summation is taken over all particles of the body. The inertia of the wind system is made up of the inertia of the turbine rotor and the inertia of the induction generator. This inertia is essential in understanding the torque equation of the system. The inertia of a wind turbine will be strongly dependent on the size and rated power of the turbine. A representative approximation of the inertia of a three bladed wind turbine, assuming that the mass middle point is about 1/3 of the radius r, is shown in (3-13). [43]

$$J = 3 \cdot m_b \cdot \left(\frac{r}{3}\right)^2 = \frac{1}{9} \cdot m_r \cdot r^2$$

(3-13)

where m_b is the mass of one of the rotor blade and m_r is the total mass of the rotor. The approximate relation between rotor diameter and rated power of MW class wind turbines is given by (3-14), whereas the approximation between rotor mass and diameter is given by (3-15). [43]

$$P_r = 195 \cdot {d_r}^{2.155}$$

(3-14)

$$m_r = 0.486 \cdot {d_r}^{2.6}$$

(3-15)

where P_r is the rated power of the turbine in MW, d_r is the diameter of the rotor in meters. Combining (3-14) and (3-15) , (3-16) can be derived to relate rotor mass and rated power.

$$m_r = 14500 \cdot {P_r}^{1.2}$$

(3-16)

From (3-10) to (3-16), the total stored energy E in the rotating mass can be derived as in (3-17) and approximated in (3-18).

$$E = \frac{1}{18} \cdot m_r \cdot r^2 \cdot {\omega_m}^2$$

(3-17)

$$E = 5.2 \times 10^6 \cdot P^{1.2}$$

(3-18)

Differences between the supplied and demanded power will immediately result in a change in the rotational speed of the generator. The rate of change of this speed depends on the amount of discrepancy between the power from the wind and the power that is transferred through the air gap to the stator as well as the rotational mass or inertia of the generator. This difference in power is balanced with the stored energy in the rotating mass as explained above. The rate of change of speed can be defined by (3-19).

$$\frac{\partial \omega_r}{\partial \tau} = \frac{T_W - T_g}{J}$$

(3-19)

Written as a function of power instead of torque will produce (3-20).

$$\frac{\partial \omega_r}{\partial \tau} = \frac{P_W - P_g}{J\omega_r}$$

(3-20)

Hence, from (3-19) and (3-20), the more inertia the generator has, the less rotor speed will change during an imbalance of power. With the larger value of inertia, speed and voltage stability can be better achieved and the system can be kept stable following a disturbance.

In contrast with the decoupled variable speed system, in fixed speed wind system where the turbine is directly connected to the power system, the inertia of the generator is 'seen' by the system and available to help stabilize the system in fault clearing time. However, the total inertia damps the system response, which in turn act as an impediment to reduce the possibility of the system to achieve maximum possible efficiency and hence makes it more difficult for the system to operate at optimum operating point. Furthermore, as can be seen from the equations, in steady state analysis, the value of inertia doesn't influence can be ignored in the discussion.

3.3 Induction Generation Theory and Modelling

The basic principle of induction machine is the utilization of electromagnetic induced in the air gap to energize either the rotor, when operating as a motor, or the stator, when operating as a generator. [6, 20] An induction machine is essentially a transformer with rotating secondary winding. The rotation speed however is not the same as the speed of the stator field. The difference is called the slip, which greatly influence the produced torque.

The induction machine can be classified through the structure of its rotor. Some induction machine uses cast iron rotor bars laid into slots and shorted at either end by rings. This type is referred to as the squirrel cage rotor. The other type is wound rotor induction machine. This type of machine has a complete set of three-phase winding that are mirror images of the stator winding. The winding is connected to slip rings and shorted by brushes. The wound rotor induction machine rotor current is accessible at the brushes, which makes it possible for extra impedances to be inserted to alter the machine's torque speed relationship. However, wound rotor induction machine is more expensive and requires more maintenance compared to cheap and rugged squirrel cage induction machine.

The use of SCIG in wind energy generation is widely accepted as a simple and cheap option, as it is reliable and requires very little maintenance due to its brushless rotor. Hence, it offers significant cost advantage over other type of generators. However, the capability of SCIG to produce power is proportional to its consumption of reactive power, hence to be able to improve the power transfer of induction generator driven WECS, an appropriate reactive power support need to be included.

3.3.1 Steady State SCIG model

Theoretical model of squirrel cage induction generator is well established. The induction machine modelled through its per-phase equivalent circuit is widely utilised for steady state analysis as shown in Figure 3-3.

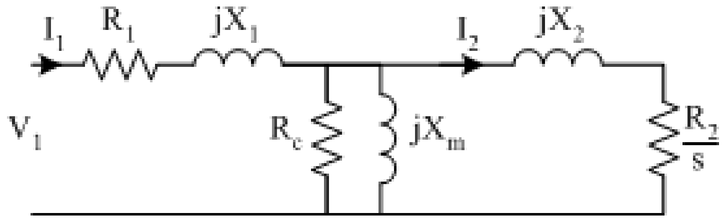


Figure 3-3 Per phase equivalent circuit of induction machine [44]

Where R_1 is the stator resistance, X_1 is the stator leakage reactance, R_2 is the rotor resistance referred to the stator side, X_2 is the rotor leakage reactance referred to the stator side, R_c is the core loss resistance and X_m is the magnetizing reactance. The parameters of this equivalent circuit can be found through the no-load test and locked rotor test. [20, 45] S is defined to be the slip, which is shown in (3-21).

$$S = \frac{n_{sync} - n_m}{n_{sync}} = \frac{\omega_{sync} - \omega_m}{\omega_{sync}}$$

(3-21)

Although the per-phase equivalent circuit has been a simple and effective tool in steady state analysis of induction machine, it is not appropriate to be used in predicting the dynamic performance of the machine. [45]

3.3.2 Dynamic SCIG model

A dynamic model of three-phase induction generator can be mathematically explained by coupling the rotor and stator using the phase variables. This model is referred to as the abc model, which include differential equations with time varying coefficients that resulted from the dependence of stator and rotor inductances on rotor position. Transforming this model through some well-known transformation such as the Park's transformation, it is possible to substitute the time varying coefficient into time invariant ones. Depending on the transformation used, the time varying coefficients can be translated into various reference frames, which result in differential equations with constant variables. Moreover, it is quite common to represent the model in per-unit value where all the system's quantities are referred to a common set of base parameters. [6]

The SCIG is modelled in abc reference frame through (3-22) to (3-29)the following equations in SI unit.

$$[v_{abc,s}] = [R_s] \cdot [i_{abc,s}] + [L_s] \cdot \frac{d}{dt}[i_{abc,s}] + [M_{sr}] \cdot \frac{d}{dt}[i_{abc,s}]$$

(3-22)

$$[v_{abc,t}] = [R_r] \cdot [i_{abc,t}] + [L_t] \cdot \frac{d}{dt}[i_{abc,t}] + [\mathrm{M_{sr}}]^2 \cdot \frac{d}{dt}[i_{abc,t}]$$

(3-23)

Where,

$$[v_{abc,s}] = \begin{bmatrix} v_{a,s} \\ v_{b,s} \\ v_{c,s} \end{bmatrix} \qquad [v_{abc,r}] = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

(3-24)

$$[i_{abc,s}] = \begin{bmatrix} i_{a,s} \\ i_{b,s} \\ i_{c,s} \end{bmatrix} \qquad [i_{abc,r}] = \begin{bmatrix} i_{a,r} \\ i_{b\,r} \\ i_{c,r} \end{bmatrix}$$

(3-25)

The parameter matrices can be defined as follows:

$$[R_s] = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \qquad [R_r] = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix}$$

(3-26)

$$[L_s] = \begin{bmatrix} L_s + M_{sr} & -\frac{M_{sr}}{2} & -\frac{M_{sr}}{2} \\ -\frac{M_{sr}}{2} & L_s + M_{sr} & -\frac{M_{sr}}{2} \\ -\frac{M_{sr}}{2} & -\frac{M_{sr}}{2} & L_s + M_{sr} \end{bmatrix}$$

(3-27)

$$[L_r] = \begin{bmatrix} L_r + M_{sr} & -\frac{M_{sr}}{2} & -\frac{M_{sr}}{2} \\ -\frac{M_{sr}}{2} & L_r + M_{sr} & -\frac{M_{sr}}{2} \\ -\frac{M_{sr}}{2} & -\frac{M_{sr}}{2} & L_r + M_{sr} \end{bmatrix}$$

(3-28)

$$[M_{sr}] = \begin{bmatrix} \cos\theta & \cos\left(\theta + \frac{2\pi}{\theta}\right) & \cos\left(\theta - \frac{2\pi}{\theta}\right) \\ \cos\left(\theta - \frac{2\pi}{\theta}\right) & \cos\theta & \cos\left(\theta + \frac{2\pi}{\theta}\right) \\ \cos\left(\theta + \frac{2\pi}{\theta}\right) & \cos\left(\theta - \frac{2\pi}{\theta}\right) & \cos\theta \end{bmatrix}$$

(3-29)

The mutual inductance and torque are defined as shown in (3-30).

$$L_m = \frac{3}{2} M_{sr} \qquad\qquad T_{im} = P \cdot [i_{abc\ r}]^r \cdot \frac{d}{d\theta}[M_{sr}] \cdot [i_{abc\ t}]$$

(3-30)

The same model in DQ reference frame is shown below.

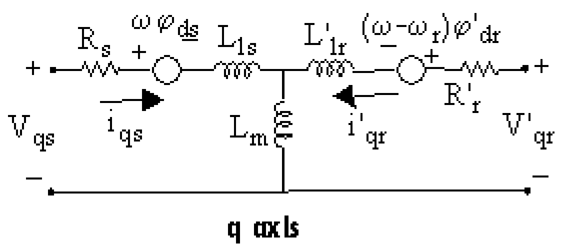


Figure 3-4 Q reference frame

$V_{qs} = R_s i_{qs} + d\varphi_{qs}/dt + \omega\varphi_{ds}$

$V_{ds} = R_s i_{ds} + d\varphi_{ds}/dt - \omega\varphi_{qs}$

$V'_{qr} = R'_r i'_{qr} + d\varphi'_{qr}/dt + (\omega - \omega_r)\varphi'_{dr}$

$V'_{dr} = R'_r i'_{dr} + d\varphi'_{dr}/dt - (\omega - \omega_r)\varphi'_{qr}$

$T_e = 1.5p(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds})$

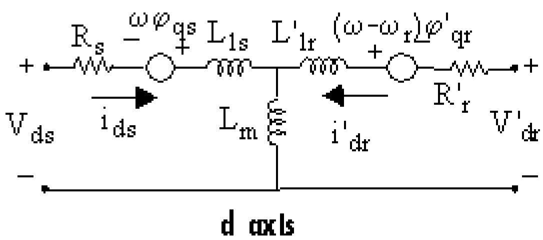


Figure 3-5 D reference frame

ω — Reference frame angular velocity

ω_r —Electrical angular velocity

$\varphi_{qs} = L_s i_{qs} + L_m i'_{qr}$

$\varphi_{ds} = L_s i_{ds} + L_m i'_{dr}$

$\varphi'_{qr} = L'_r i'_{qr} + L_m i_{qs}$

$\varphi'_{dr} = L'_r i'_{dr} + L_m i_{ds}$

$L_s = L_{ls} + L_m$

$L'_r = L'_{lr} + L_m$

The conventional losses in an induction generator model include the stator and rotor iron conductor losses, magnetic loss and friction and windage loss. In a practical induction machine, due to the non-ideal nature of the machine, there is an additional loss component that is generally termed the stray load loss. [20]

3.3.3 Torque in both models

The torque equation for the induction generator is the same in both static and dynamic model and can be defined as shown in (3-31)and (3-32).

$$\frac{d}{dt}\omega_m = \frac{1}{2 \cdot H}(T_e - F \cdot \omega_m - T_m)$$

(3-31)

$$\frac{d}{dt}\theta_m = \omega_m$$

(3-32)

3.4 Voltage Control of IG and its relationship with Torque and Power

The principal of voltage control in induction motor is a well-established theory. Voltage control can be seen as an avenue to implement the speed control of induction machine. This control can be utilised to maintain efficiency when the motor's load varies over a large range. Figure 3-6 is the torque speed characteristic of a typical induction motor at various voltages. It can clearly be seen that altering the voltage results in the vertical shift of the torque speed curve of the induction motor.

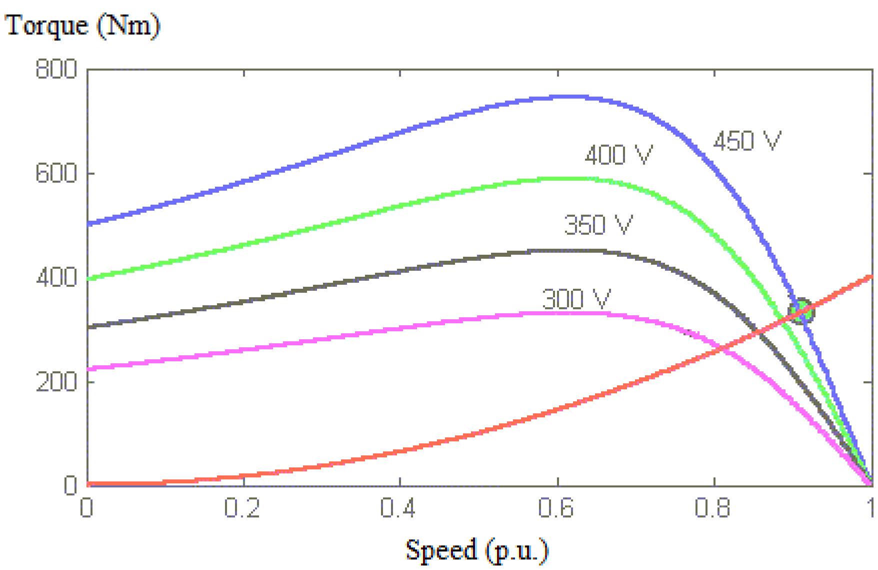


Figure 3-6 Torque speed curve of an induction motor at various voltages [46]

The implementation of stator voltage control to maintain the efficiency of the induction machine when loaded with various load can be explained in terms of motor losses, especially the iron and copper losses.

Iron losses consist of hysteresis losses and eddy current losses. At constant frequency the hysteresis loss is proportional to maximum flux density in the air gap, B whereas the eddy current loss is proportional to B^2. When the applied voltage is kept constant, the maximum flux density remains constant. Thus, as the load is decreased, voltage remaining constant, the iron loss constitutes a greater percentage of the output. This results in poor efficiency. This efficiency can be improved by reducing the applied voltage to the motor. This will be especially effective if the running slip of the motor is in the steep region of the torque-slip curve around the zero slip. When the applied voltage is reduced, the load torque intersects the motor curve at a new point. Due to the steepness of the curve, the small change in speed will result in a more significant change in torque. [47] Furthermore the reduction in voltage results in and initial decrease of currents and copper losses. However, there is a point where decreasing the voltage further will result in an increase in copper loss and subsequently total motor losses. Hence, there is one particular voltage level at which the total losses in the motor is minimum and hence the efficiency maximized. [47]

Torque is dependent on V^2. The variation of the speed torque curves with respect of the applied voltage can be derived. From the curves it can be seen that the slip at maximum torques remain relatively constant with changes in voltage and the speed range for stable operation remain constant.

From the principals of motor, it can be deduced [1] that the efficiency of a lightly loaded induction motor can be very substantially improved by controlling the voltage applied to it. In addition, controlling the voltage also improves the power factor at which the motor operates. It has been proved that similar to the induction motor, in an induction generator, the efficiency of the machine can be varied by controlling the stator voltage. Furthermore, there is always an optimum voltage for every torque at which the efficiency and hence power is maximum, as shown by point A in Figure 3-7. A pre-calculated optimum input voltage depending on the wind can be utilized in the control system [2]. Extension of this principle has been implemented to a variable speed wound rotor induction generator implemented in a wind energy conversion system through the utilization of variable AC regulator and variable external rotor resistor [2].

Implementing the same principle, [3] it can be deduced that wind turbine output power depends on both wind and rotation speeds, which is indirectly dependant on the voltage. The relationship between voltage and power is shown in Figure 3-7.

Point A in Figure 3-7 indicates the optimum operating voltage of a particular bus in a system which illustrate the existence of operating point that gives optimum power transfer capability of the system.

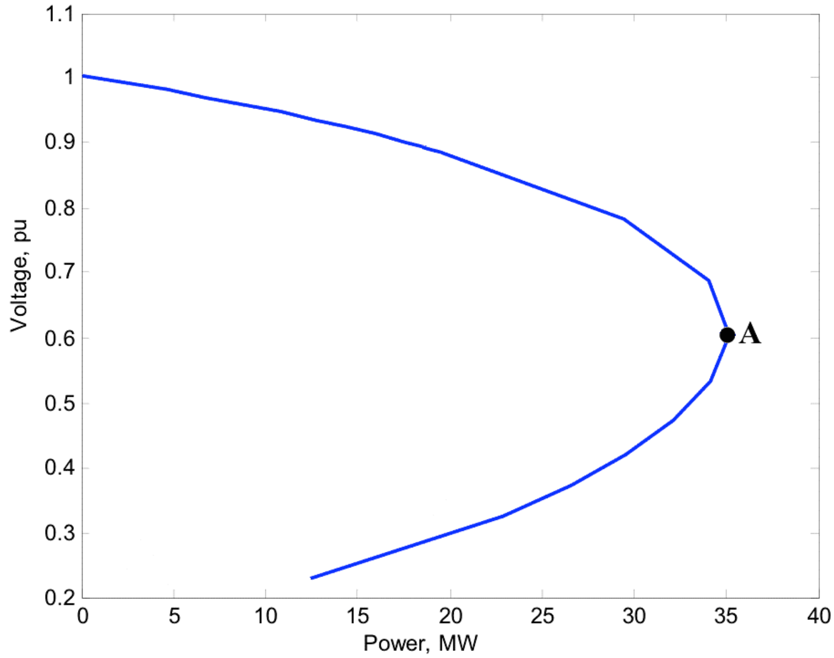


Figure 3-7 Voltage and power relationship

Various voltage control methods can be utilised to achieve the improvement in efficiency for a fixed speed WECS. One method can be implemented through reactive power control. The utilisation of dynamic reactive power support in fixed speed system has been reported [4] to be able to dampen voltage fluctuation by mitigating P and Q fluctuation. In another words, voltage control can be achieved through P and Q control. [5] Although the regulation of voltage magnitude has much more influence over the reactive power flow than the active power flow, regulating the magnitudes of sending and receiving ends voltages can also control power flow in transmission line, subject to grid allowance of voltage variation, which in this proposed system will be supported by the utilisation of the OLTC transformer [6]. Moreover, stator voltage control of the induction generation can extend the operating region of the system, which translates to further improvement of the power transfer.

The effectiveness of voltage control scheme in improving the power transfer capability of the system is illustrated in the following graphs. The intersection between the wind turbine power curve and the induction generator power speed characteristic denotes the operation point of the wind energy conversion system. Wind turbine power curve shifts depending on the wind speed at any given time. Hence, in conventional system, the intersections between these curves with the induction generator curve govern the operating point of the system. However, by performing voltage control, it is possible for the operating points to be altered due to the shift in induction generator curve. By altering voltage, the induction generator curve shifts vertically enabling new operating points to be followed by the system. The effectiveness of the voltage control depends on the shape of these graphs and where do they intersect.

The red lines are power from the induction generator with low (80% rated voltage), medium (rated voltage) and high (120% rated voltage). The blue lines are the power from the wind turbine at low wind speed (5 m/s), medium (8 m/s) and high (11 m/s). So instead of operating along one red curve, in the proposed scheme the system can operate on various red curves and due to this the power transferred can be improved.

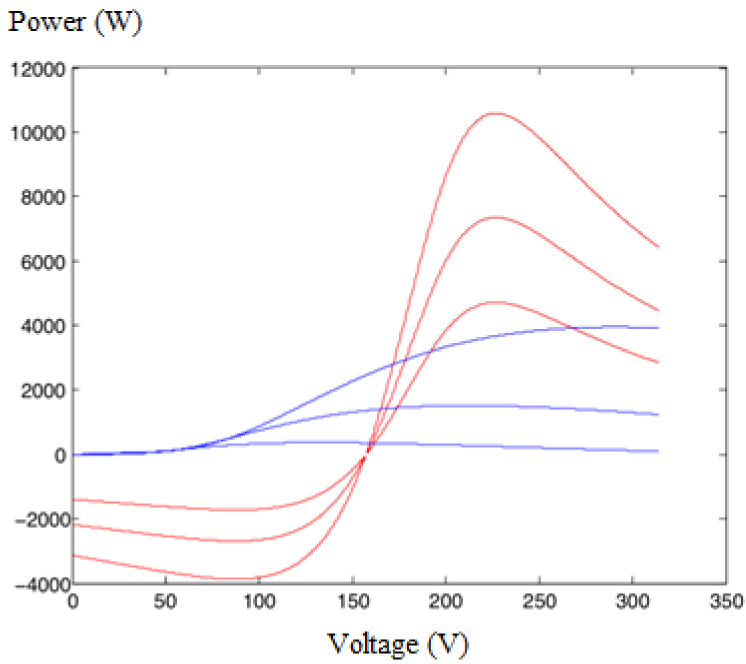


Figure 3-8 Voltage Control Principle

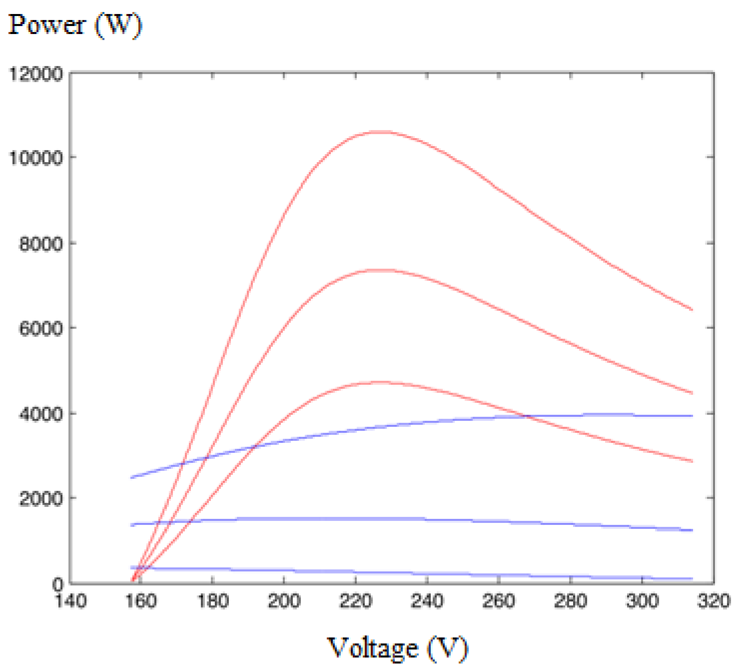


Figure 3-9 Voltage Control Principle (Generator Mode)

The relationship between terminal voltage of the induction generator and rotor speed as well as the torque and power is shown in (3-33).

$$T_L - T_e = J\frac{d\omega_{generator\_rotor}}{dt}$$

(3-33)

In steady state, the rate of change of the generator rotor speed is zero.

$$\frac{d\omega_{generator\_rotor}}{dt} = 0$$

$$T_L = T_e$$

(3-34)

The wind turbine in this case is acting as a generating load

$$P_{wind\_turbine} = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot {U_w}^3 cp(\lambda)$$

(3-35)

$$\lambda = \frac{\omega_{turbine\_rotor} R}{U_w}$$

(3-36)

$$cp(\lambda) = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{\frac{c_3}{\lambda_1}} + c_6 \lambda$$

(3-37)

Where,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + c_7 \beta} - \frac{c_8}{\beta^3 + 1}$$

(3-38)

$$T_{turbine} = \frac{P_{wind\_turbine}}{\omega_{turbine\_rotor}} = \frac{\frac{1}{2} \rho \pi R^3 cp(\lambda)}{\omega_{turbine\_rotor}}$$

(3-39)

$$T_L = -\frac{T_{turbine}}{gearbox} = -\frac{P_{wind\_turbine} / \omega_{turbine\_rotor}}{gearbox}$$

(3-40)

$$= -\frac{P_{wind\_turbine}}{\omega_{turbine\_rotor} \times gearbox}$$

(3-41)

$$= -\frac{P_L}{\omega_{generator\_rotor}} = -\frac{\frac{1}{2}\rho\pi R^2 {U_w}^3 cp(\lambda)}{\omega_{generator\_rotor}}$$

(3-42)

With

$$\omega_{generator\_rotor} = \omega_{turbine\_rotor} \times gearbox$$

(3-43)

So load torque is affected by the generator rotor speed, which is mechanically coupled to the rotor of the induction generator through a gearbox, assuming that the system is a lossless system with power produced by the wind turbine directly conveyed to the rotor of the induction generator.

$$P_e = 3{I'_R}^2 \cdot \left(\frac{R'_R}{s}\right)$$

(3-44)

Ignoring the magnetisation inductance for simplification purpose,

$$I'_R = \frac{U_R}{\sqrt{\left(\frac{R'_R}{s}\right)^2 + {X'_R}^2}}$$

$$= \frac{U_s}{\sqrt{\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2}}$$

(3-45)

$$P_e = \frac{3{U_s}^2 \left(\frac{R'_R}{s}\right)}{\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2}$$

(3-46)

$$T_e = \frac{P_e}{\omega_{generator\_stator}} = \frac{P_e}{\omega_{synchronous}}$$

(3-47)

$$\omega_{synchronous} = \frac{2\pi}{60} n_{synchronous} = \frac{2\pi}{60} \times \frac{120f}{poles}$$

$$= \frac{4\pi f}{poles} = \frac{2\pi f}{polepairs}$$

(3-48)

Hence,

$$T_e = \frac{3 \cdot polepairs}{2\pi f} \frac{{U_s}^2 \left(\frac{R'_R}{s}\right)}{\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2} - \frac{\frac{1}{2}\rho\pi R^2 {U_w}^3 cp(\lambda)}{\omega_{generator\_rotor}}$$

$$= \frac{3 \cdot polepairs}{2\pi f} \frac{{U_s}^2 \left(\frac{R'_R}{s}\right)}{\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2}$$

$$- \left(\frac{1}{2}\rho\pi R^2 {U_w}^3 cp(\lambda)\right) (2\pi f) \left[\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2\right]$$

$$= 3 \cdot polepairs\left(\omega_{generator\_rotor}\right) \left[{U_s}^2 \left(\frac{R'_R}{s}\right)\right]$$

$$- \left(\rho\pi R^2 f {U_w}^3 cp(\lambda)\right) \left[\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2\right]$$

$$= 3 \cdot polepairs\left(\omega_{generator\_rotor}\right) \left[{U_s}^2 \left(\frac{R'_R}{s}\right)\right]$$

(3-49)

with slip being defined as

$$s = \frac{\omega_{synchronous} - \omega_{generator\_rotor}}{\omega_{synchronous}}$$

(3-50)

so

$$\omega_{generator\_rotor} = (1-s)\omega_{synchronous} = (1-s)\left(\frac{2\pi f}{polepairs}\right)$$

(3-51)

The equation becomes

$$-\left(\rho\pi^2 R^2 f U_w{}^3 cp(\lambda)\right)\left[\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2\right] = 3 \cdot polepairs(1-s)\left(\frac{2\pi f}{polepairs}\right)\left[U_s{}^2\left(\frac{R'_R}{s}\right)\right]$$

$$-\left(\rho\pi^2 R^2 f U_w{}^3 cp(\lambda)\right)\left[\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2\right] = 6\pi f(1-s)U_s{}^2\left(\frac{R'_R}{s}\right)$$

$$-\left(\rho\pi R^2 U_w{}^3 cp(\lambda)\right)\left[\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2\right] = 6(1-s)U_s{}^2\left(\frac{R'_R}{s}\right)$$

$$U_s = \sqrt{\frac{\left(\rho\pi R^2 U_w{}^3 cp(\lambda)\right)\left[\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2\right]}{6(s-1)\left(\frac{R'_R}{s}\right)}}$$

(3-52)

Implementing this equation in Matlab® and it produces the following figure. As can be seen from the equation, the terminal voltage depends on not only the speed of the generator but also the wind speed and *cp* value. Furthermore, *cp* value is a function of tip speed ratio, which in turn is a function of wind speed. Hence, wind speed has significant effect in the relationship between voltage and speed.

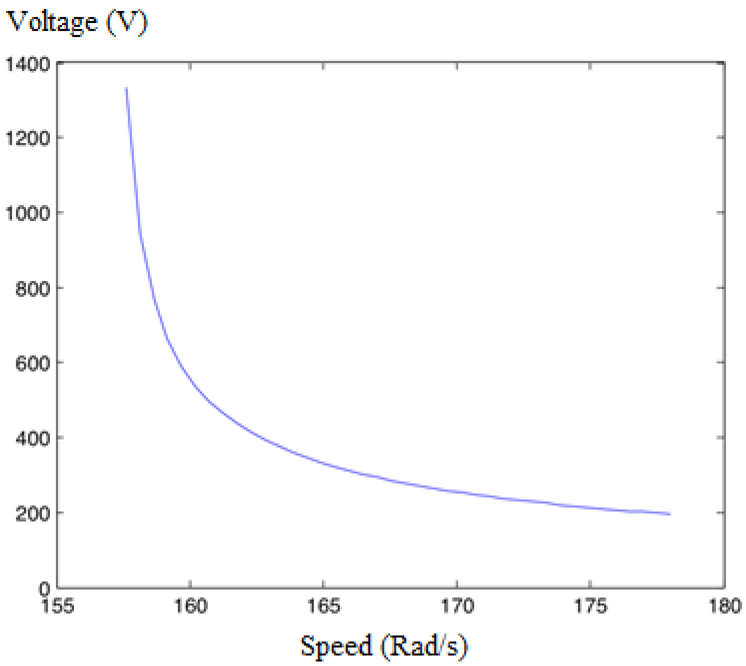


Figure 3-10 Voltage Speed Relationship

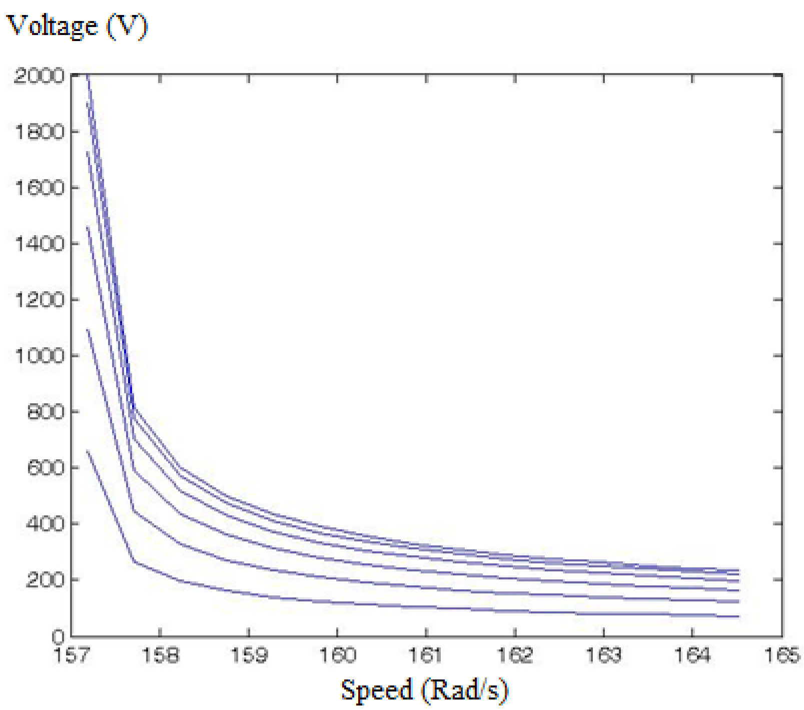


Figure 3-11 Voltage speed relationship at 5m/s,7m/s,9m/s,11m/s,13m/s and 15m/s

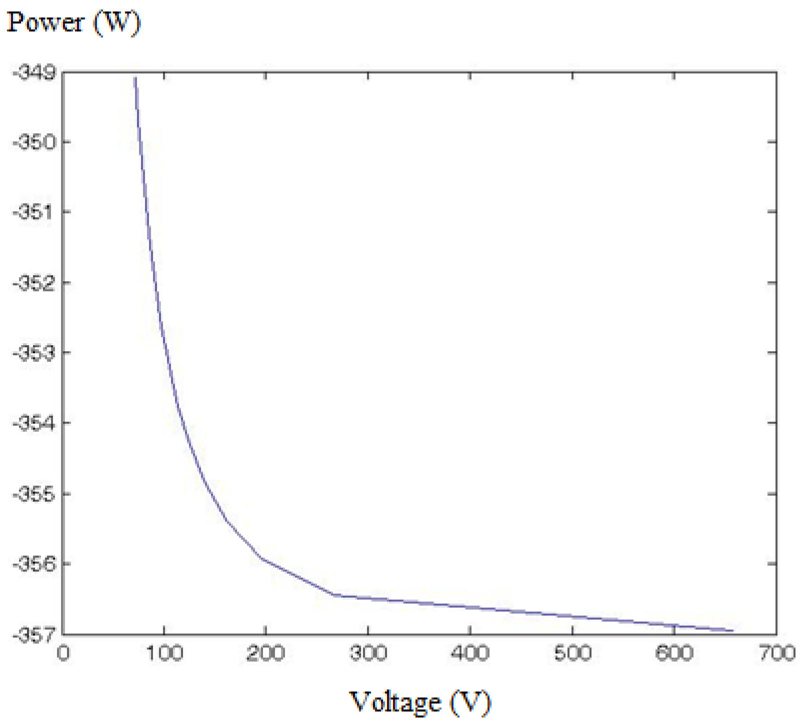


Figure 3-12 Power Vs Voltage for wind speed at 5m/s

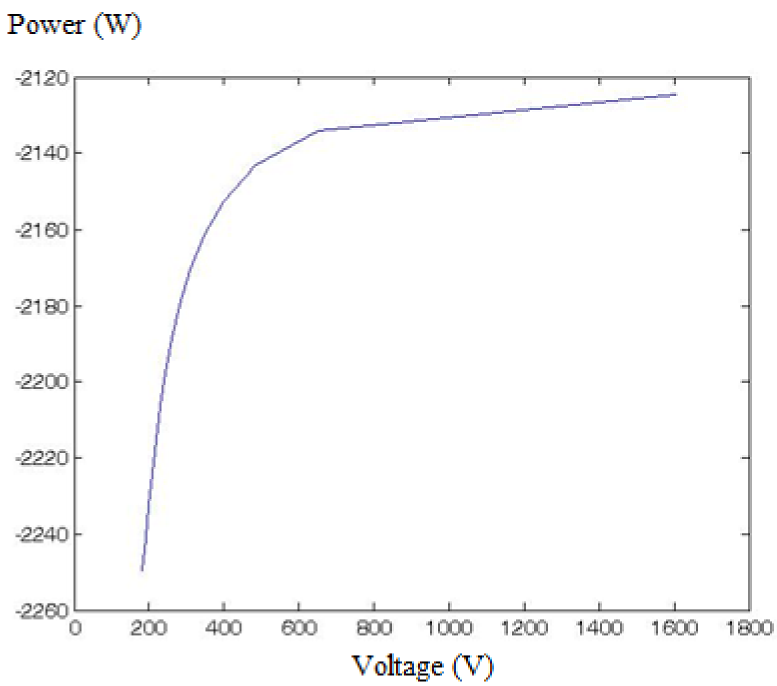


Figure 3-13 Power Vs Voltage for wind speed at 10m/s

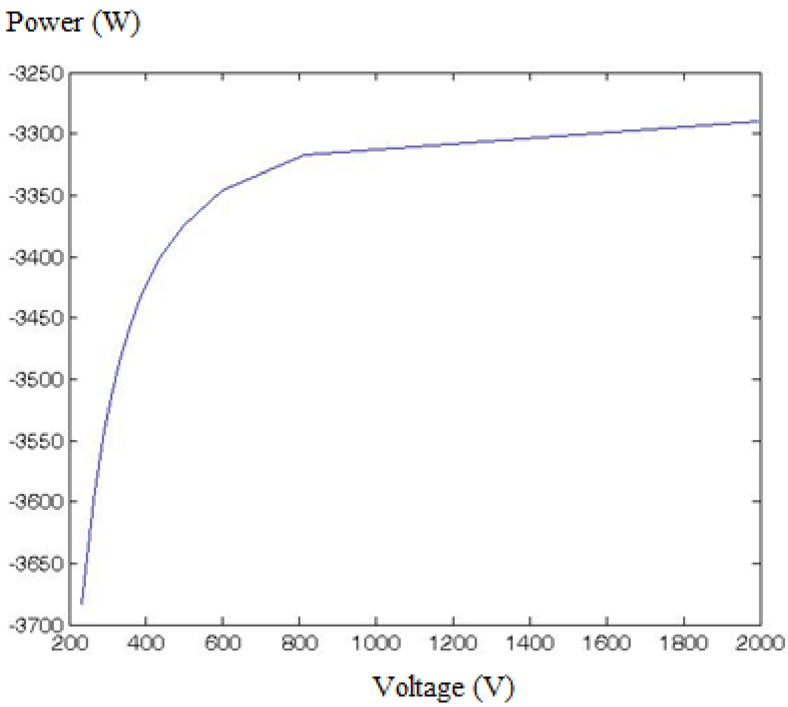


Figure 3-14 Power Vs Voltage for wind speed at 15m/s

3.5 Reactive Power Compensation Needed

An induction machine can work as a generator if the required amount of reactive power is supplied to sustain the excitation requirement, while the rotor speed is maintained by some prime mover above the synchronous speed. When the generator is connected to the grid, theoretically, it is possible for this reactive power requirement to be supplied by the grid. However, due to the connection regulation, it is required that at the point of common coupling a certain power factor is maintained. This means that the generator is not allowed to take reactive power from the grid and have to be self-sufficient through the utilization of excitation capacitors.

The voltage and current of the excitation capacitors in DQ reference frame can be expressed in (3-53) and (3-54).

$$i_{cq} = \left(\frac{C}{\omega_b}\right) p\left(v_{qs}\right) + \omega_e C v_{dc}$$

(3-53)

$$i_{cd} = \left(\frac{C}{\omega_b}\right) p(v_{ds}) + \omega_e C v_{qc}$$

(3-54)

Reactive power support can be realised through various different configurations. It can be implemented through series or shunt compensation. [23, 24]

3.5.1 Relationship between terminal voltage and reactive power

To explain the relationship between terminal voltage of the induction generator and reactive power consumed by the generator, the Γ model is utilised. The reactive power consumed can be broken up into two components: one caused by the leakage inductances in the rotor and stator windings of the generator and one caused by the magnetisation inductance. It was found that this magnetisation inductor consumed most part of the reactive power due to its significantly larger size compared to the leakage inductances.

$$Q_i = 3{I'_g}^2\left(X_S + X'_g\right)$$

$$= \frac{3{U_s}^2(X_s + X'_g)}{\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2}$$

(3-55)

$$Q_m = \frac{3{U_s}^2}{X_m}$$

(3-56)

$$Q = Q_i + Q_m$$

$$= \frac{3{U_s}^2(X_s + X'_R)}{\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2} + \frac{3{U_s}^2}{X_m}$$

$$\frac{3X_m{U_s}^2(X_s + X'_R) + 3{U_s}^2\left[\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2\right]}{\left[\left(R_s + \frac{R'_R}{s}\right)^2 + (X_s + X'_R)^2\right]X_m}$$

(3-57)

At 5m/s of wind Speed

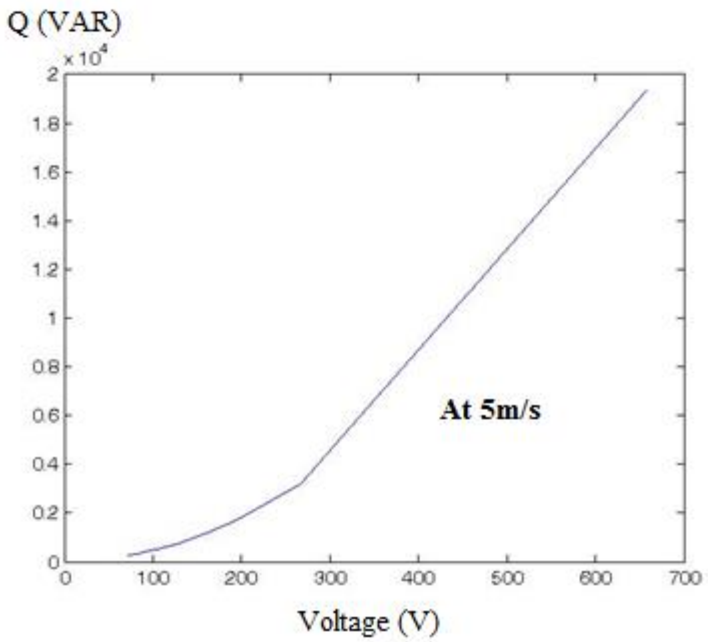
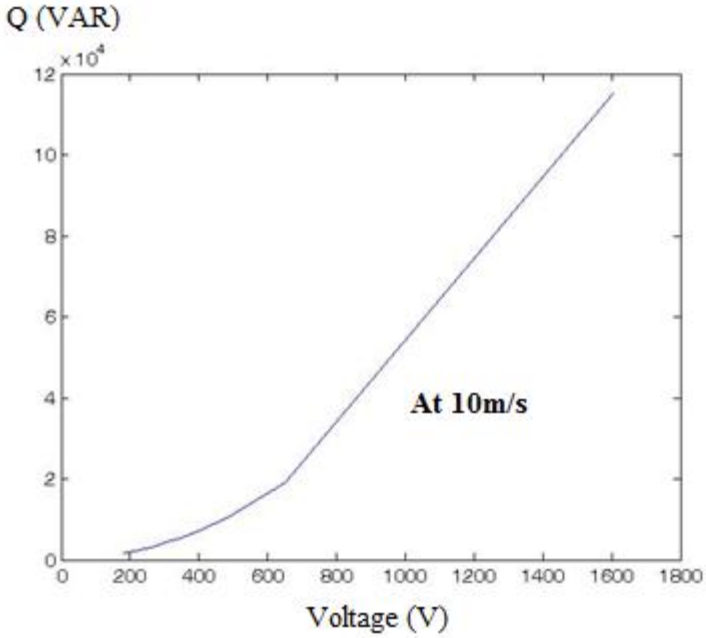


Figure 3-15 Q Vs V for wind speed at 5m/s, 10m/s and 15m/s

(To be continued in the next page)

At 10m/s of wind Speed



At 15m/s of wind Speed

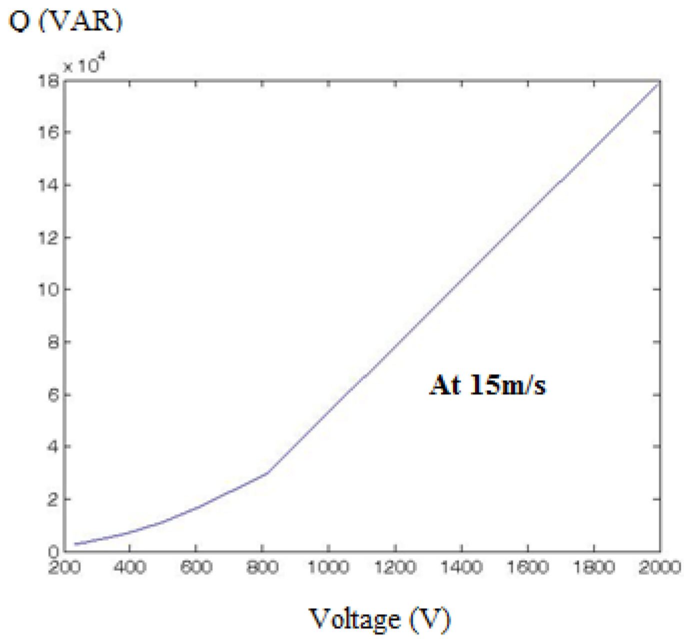
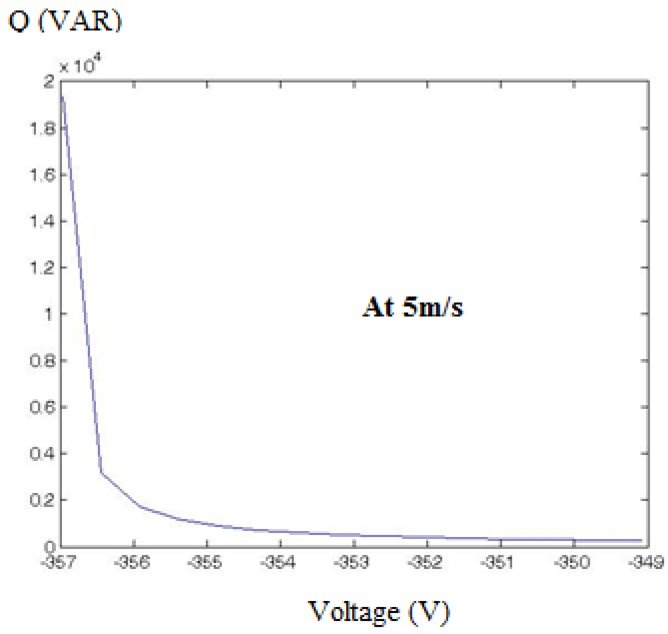


Figure 3-15 Q Vs V for wind speed at 5m/s, 10m/s and 15m/s

At 5m/s of wind Speed



At 10m/s of wind Speed

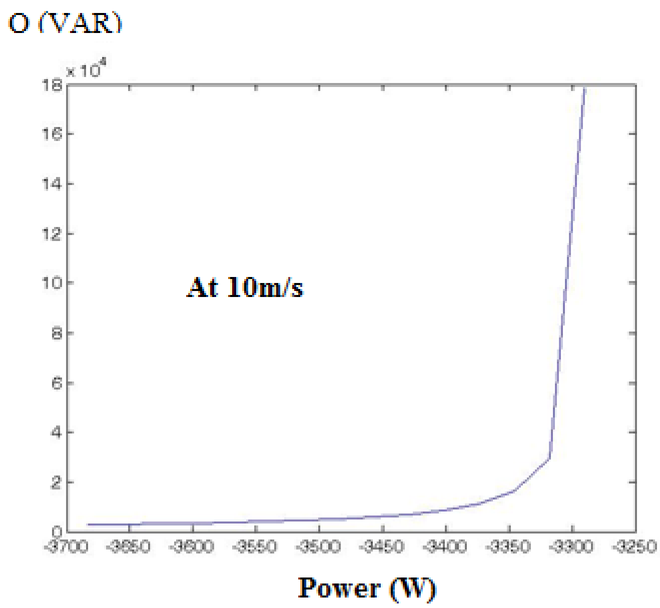


Figure 3-16 Q Vs P for wind speed at 5m/s, 10m/s and 15m/s

(To be continued in the next page)

At 15m/s of wind Speed

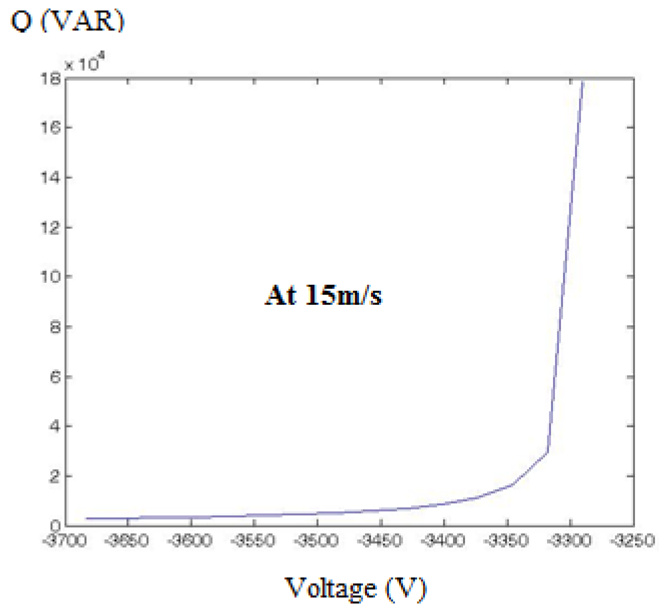


Figure 3-16 Q Vs P for wind speed at 5m/s, 10m/s and 15m/s

Figure 3-15 and Figure 3-16 depicts the relationship between real power and voltage with reactive power at different wind speed. These figures represent the relationship as mathematically derived in (3-57).

4. Test System Data

4.1 Background of Case Study

To validate the simulation model and the proposed system of this research a case study has been performed on a wind farm in China. The wind turbine is a 49.5 MW wind farm that consists of 66 wind turbine, each 750kW. The turbine is a squirrel cage induction generator and directly connected to the grid without power electronic converters.

This study gathers a wind profile from a met mast of a wind farm as well as energy produced by one of the 750kW wind turbine in the farm. The collected data is explained in the following chapters.

4.2 Wind Speed Data Collection

The wind data was collected from sensors at the met mast that was installed prior to the commissioning at the wind farm. Wind speed data is collected spanning a number of years to investigate the profile of the wind and will be used in the decision making process on the switching profile of the variable capacitors and OLTC.

These sensors were located at 10m, 30m, 50m and 70m of height. The data from the 50m met mast sensor height corresponds to the actual hub height at the wind turbines.

4.2.1 Diurnal Wind Data

Table 4-1 and Figure 4-1 illustrate the 2005 yearly average wind speed and power density for a day gathered from met mast data from the wind farm. From Figure 4-1, it can be seen, that the general trend of the wind speed and power density is correlated and minimum average wind speed occurs around dawn to morning, with 7.2m/s at 4am, 5am, 7am and 10am and the maximum average wind speed occurs in the evening, with 9.1m/s at 7pm and 8pm. Looking at this profile, the diurnal variation and characteristic is reasonably distinguishable. Although local variation must be taken into account as wind characteristic varies greatly between different geographical location, this diurnal cycle of the wind profile is beneficial in the segmentation of input for this project.

	Time (hr)																							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Average Wind Speed (m/s)	7.8	7.4	7.3	7.3	7.2	7.2	7.3	7.2	7.3	7.3	7.2	7.4	7.6	7.9	8.1	8.2	8.5	8.8	8.9	9.1	9.1	9	8.7	8.2
Wind Power (kW)	627	590	605	601	587	584	584	576	578	571	543	545	583	644	664	678	689	752	744	755	763	756	703	637

Table 4-1 2005 average wind speed and power density diurnal variation

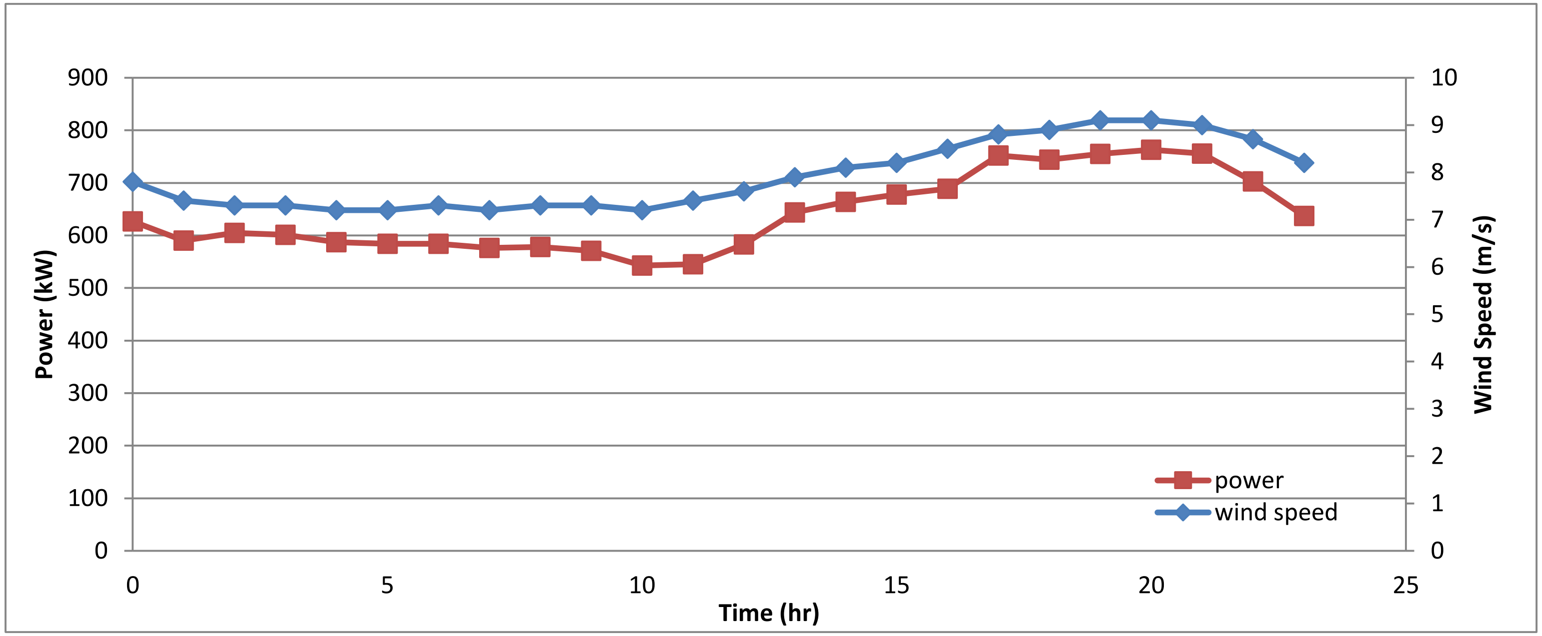
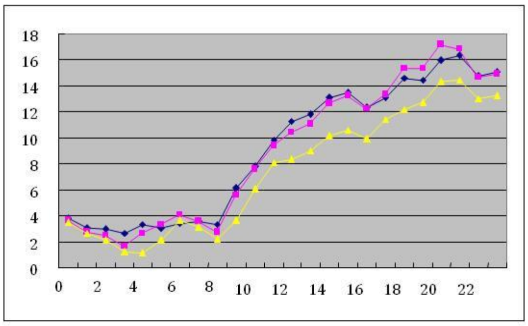


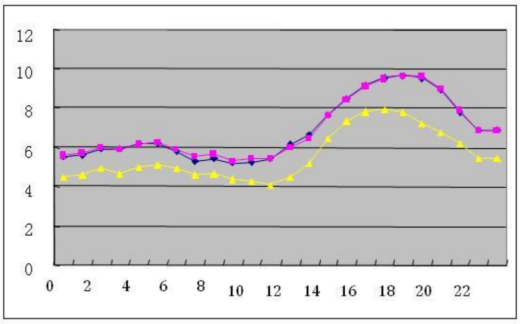
Figure 4-1 2005 average wind speed and power density diurnal variation

4.2.2 Monthly Diurnal Wind Data

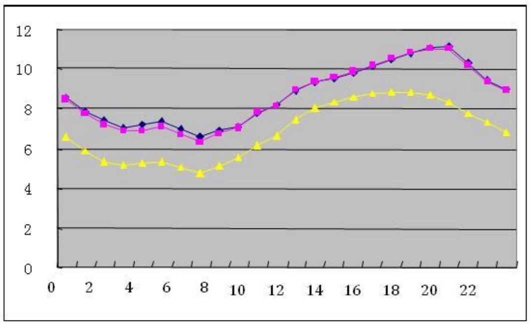
Further to the diurnal variation in the average wind speed and power density in the annual data, the wind profile was also collected to investigate the effect of monthly weather on this diurnal profile. The 2005 data is depicted with 3 different met mast height, 10m, shown with the yellow line, 50m is shown by the pink line and the 70m data is shown by the blue line. For each month in the year, the average one day diurnal wind data are shown in the following 12 graphs. The x-axis, in the following graphs, corresponds to hours (hr), whereas the y-axis represents the wind speed (m/s).



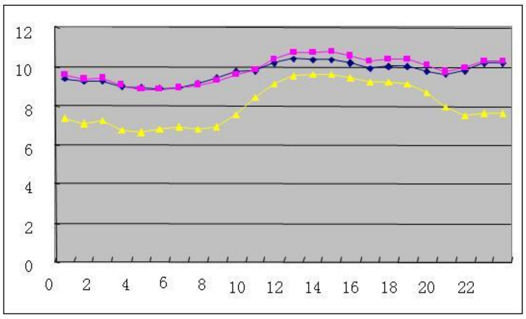
January



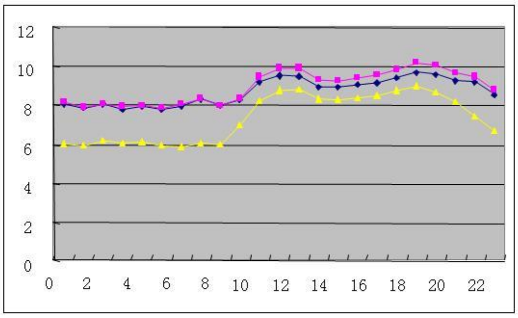
February



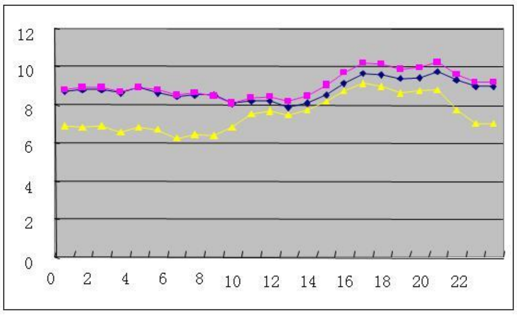
March



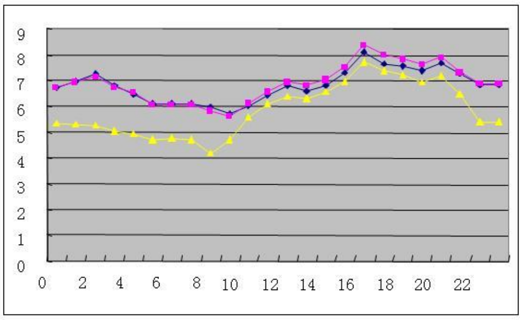
April



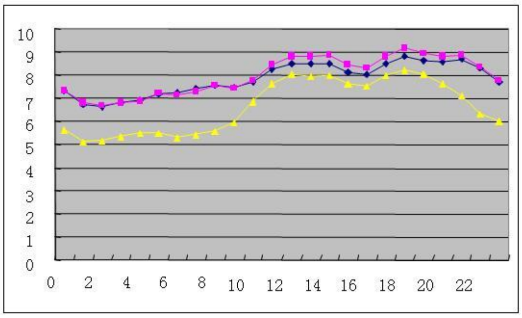
May



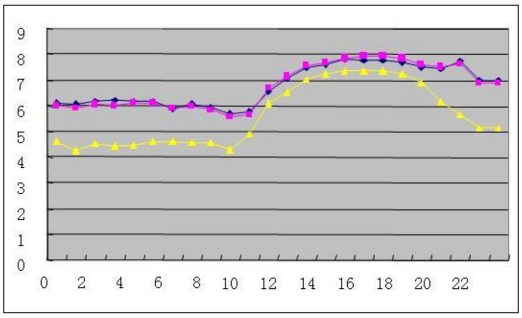
June



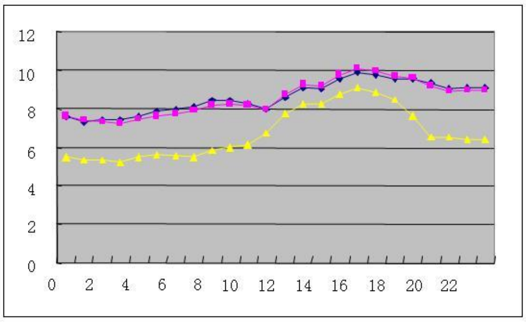
July



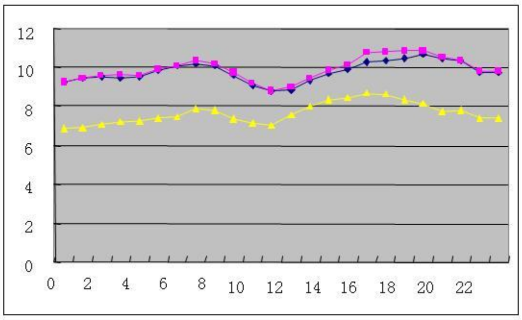
August



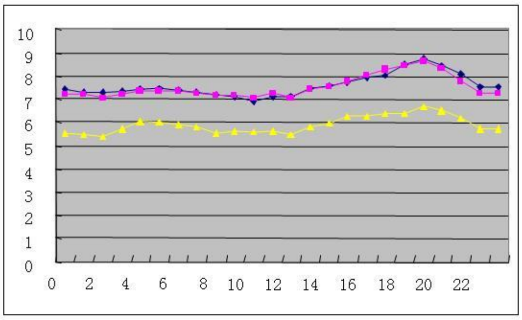
September



October

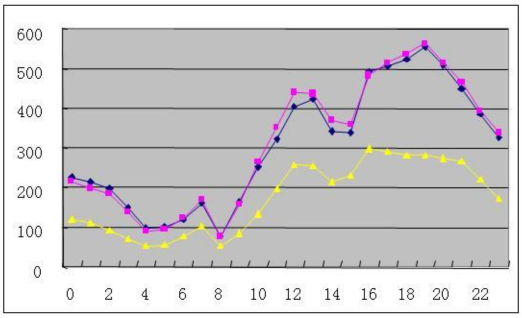


November

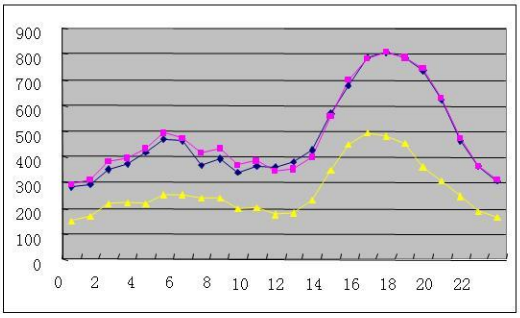


December

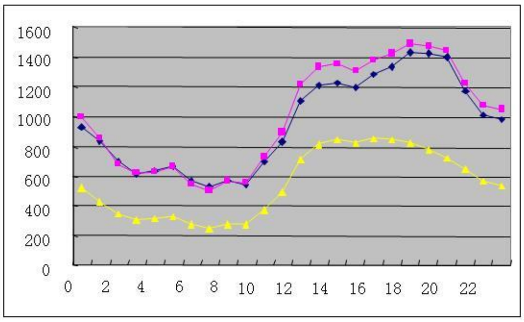
The next 12 graphs show the power density to correspond with the wind data. The x-axis, in the following graphs, corresponds to hours (hr), whereas the y-axis represents the wind power (W).



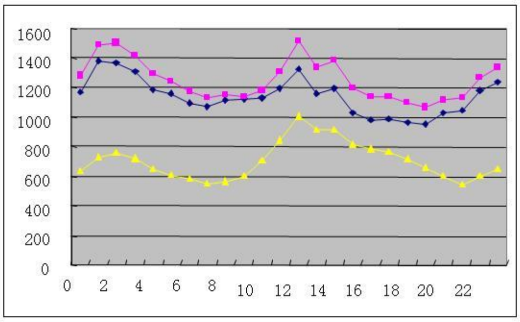
January



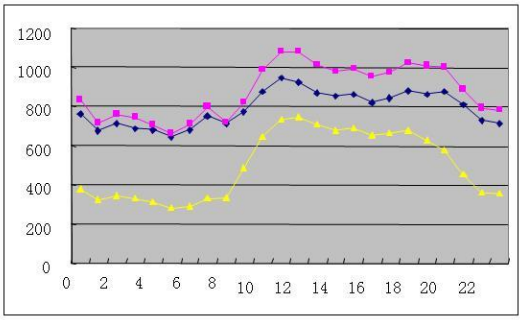
February



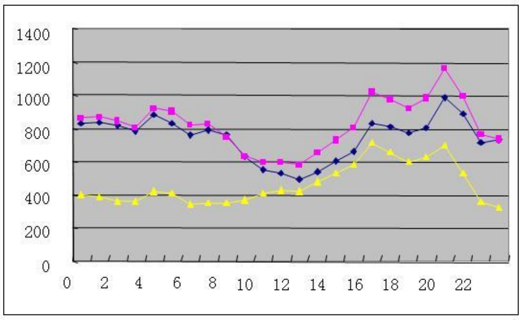
March



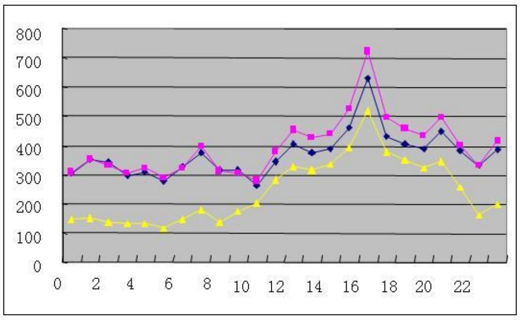
April



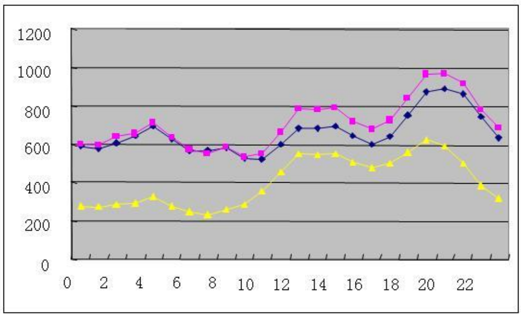
May



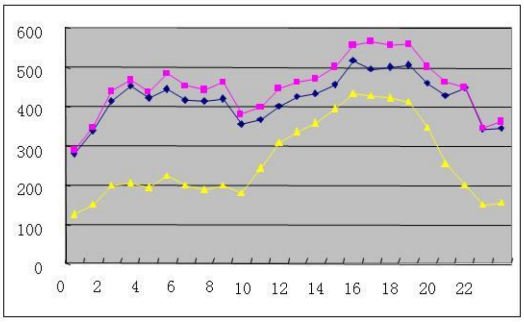
June



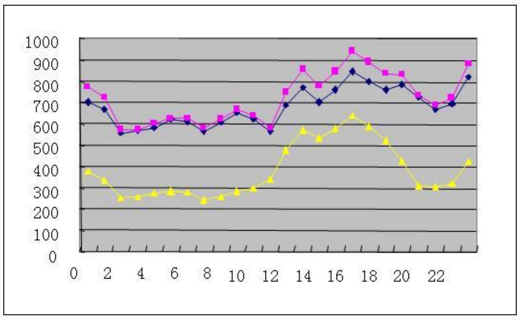
July



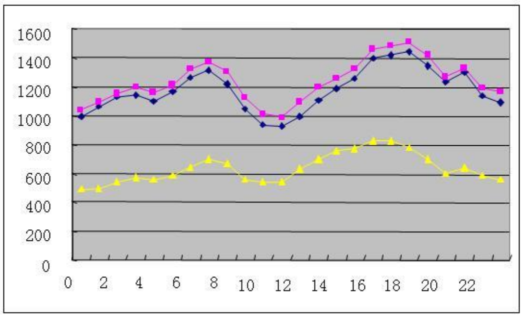
August



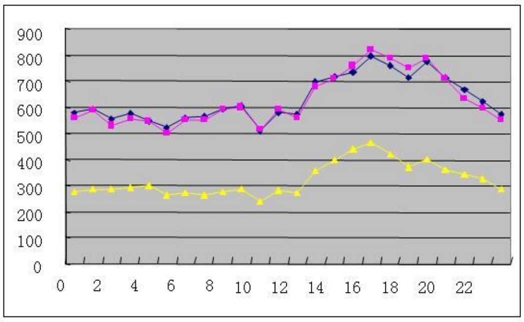
September



October



November



December

From the graphs, it can be seen that the wind speed gathered from the 50m and 70m met mast are closer in value then the data from the 10m mast. This is explainable by the wind shear theory as shown in (3-1).

Further observation from the wind profile, in this particular wind farm location in China, during the colder months between December and March, the diurnal variation is significantly more noticeable whereas the wind speed doesn't vary very much in a day of the hotter months. The month of January is generally the coldest month of the year and with the high amount of fluctuation in average wind speed. Average wind speed is lowest during the hot month of July which is directly translated in the lower power density.

The data show that diurnal variation of wind speed varies with season and time of the year. This dictates the need to adjust the wind input segmenting strategy that is used in determining the control parameter of the variable capacitor and OLTC.

4.2.3 Annual Wind Statistics

In addition to the diurnal variation of the wind, average wind speed also vary depending on the season and general weather condition.

Table 4-2 illustrates the monthly average wind speed for the year of 2001 to 2004. From Figure 4-2, it can be seen that there is a seasonal trend that define the annual average wind speed profile. Wind is generally highest during colder months, in this case study peaking at 8.1m/s average in January and lowest during the hotter month with the minimum occurring at 3.9m/s average in July. It should be noted, that this trend slightly varies from year to year and in the occurrence of extreme weather condition.

In Figure 4-3, the average monthly wind speed and power density is shown for the year of 2005. This data is gathered from measurement at the wind farm 50m hub height. In this figure, it can be seen that the trend is in agreement with that shown for the previous years.

Wind Speed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
2001	6.9	8.7	7.7	7.5	5.1	4.8	3.8	4.1	4.4	6.4	6.9	8.1	6.2
2002	7.6	7.1	8.5	6.4	5.1	4	4	4.2	5.2	5.1	6.4	8.5	6
2003	9.1	8.3	6.9	5.4	4.3	4.4	3.4	3.7	4.4	5.8	7.3	8.2	5.9
2004	8.7	7.8	6.2	5.5	4.9	4.5	4.2	4.3	4.4	6.2	7.8	7.3	6
Average Wind Speed	8.1	8	7.3	6.2	4.9	4.4	3.9	4.1	4.6	5.9	7.1	8	6

Table 4-2 Monthly average wind speed for 2001 to 2004 in m/s

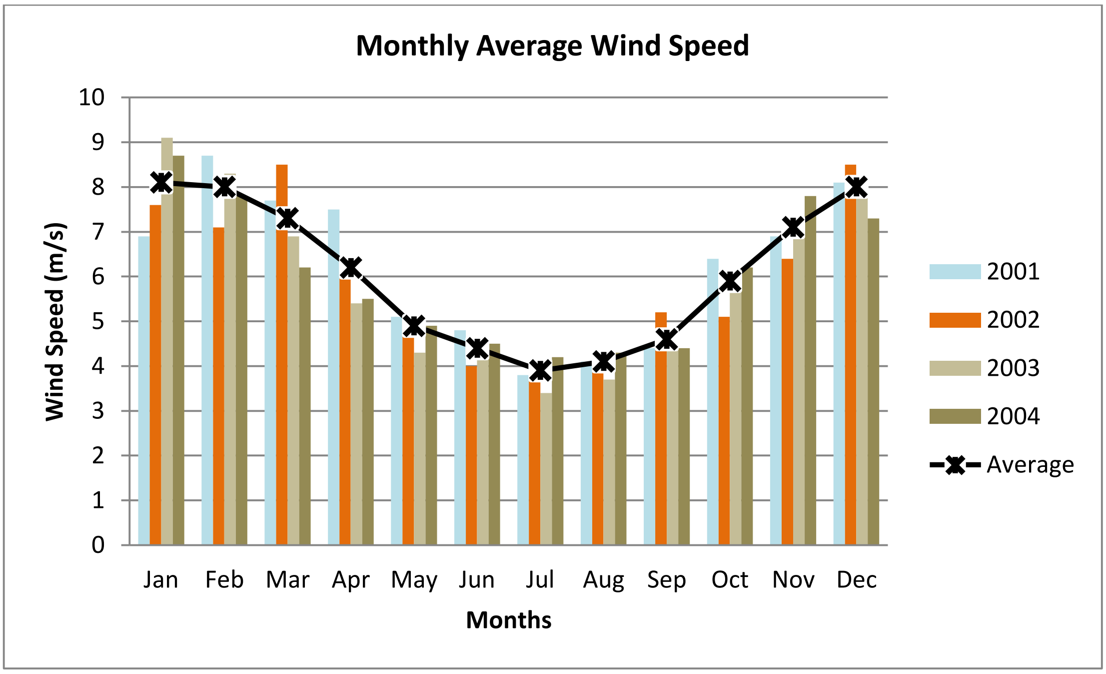


Figure 4-2 Monthly average wind speed for 2001 to 2004

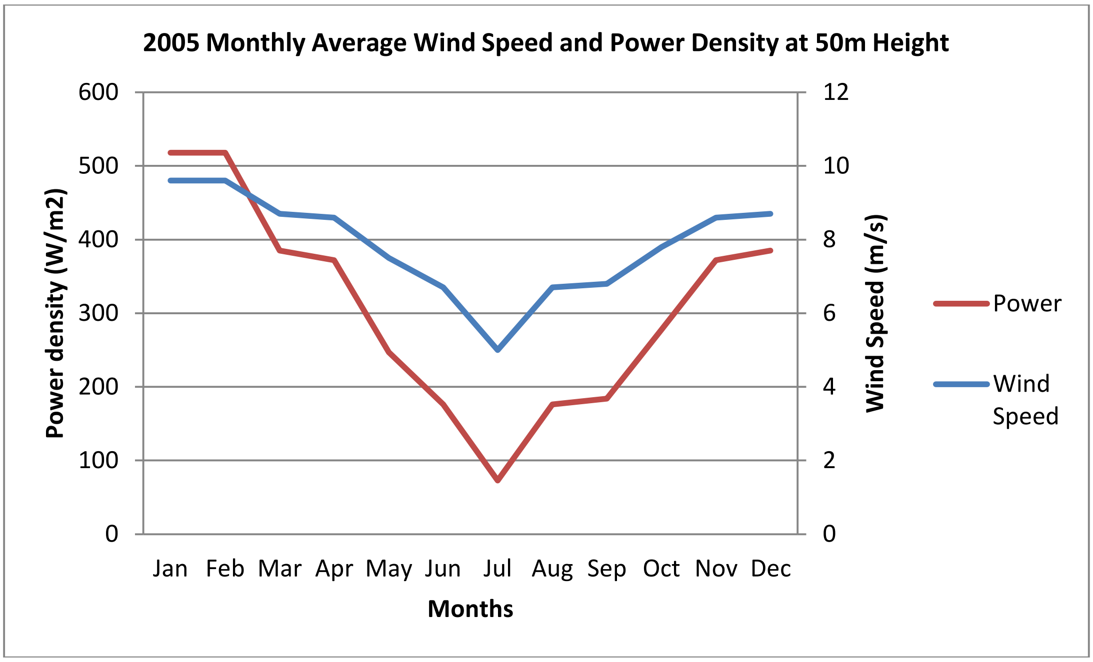


Figure 4-3 Monthly average wind speed and power density for 2005

The following tables and figures show the 2005 percentage of occurrence wind speed and wind energy data at various wind speeds and met mast heights. From Table 4-3 and Table 4-4, it can be seen that wind speed is directly related with the height of the met mast with the higher wind speed occurring more often at the 70m met mast height compared to the lower height. More wind energy is also extracted at higher wind speed with the exception of the data of above 18m/s wind speed for the 70m met mast. In this particular wind farm site, this is due to the occurrence of wind speed above the cut out wind speed at this met mast height. However, the difference between the 50m and the 70m data did not warrant the additional cost that would have been incurred by the higher hub height and hence 50m was selected as the hub height of the turbines in the wind farm.

	Wind Speed (m/s)																			
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**>18**
10m	3.7	5.7	9.8	11.8	10.8	10.2	8	6.8	7.4	5.2	4.8	4.1	3.2	2.4	1.7	1.5	1.1	0.7	0.6	0.5
30m	3.1	4.8	8.9	10.2	9.1	8.4	7.8	7.4	6.2	5.5	4.7	4.5	4.3	3.5	2.7	2.3	1.6	1.4	0.2	3.4
50m	3.2	4.4	7.5	9	8	8.3	8	7.6	6.7	6.1	5	4.5	4.3	3.9	3	2.5	1.8	1.5	1.4	3.3
70m	2.4	4.8	7.3	8.9	8.5	8.3	7.7	7.4	7.2	6.4	5.6	4.9	4.7	3.7	3.1	2.4	1.8	1.7	1.1	2.1

Table 4-3 2005 wind speed frequency

	Wind Speed (m/s)																			
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**>18**
10m	0	0	0.1	0.5	1.2	2.1	2.8	3.8	6.2	6.2	7.9	9	9.1	8.7	7.7	8.3	7.4	5.7	5.8	7.5
30m	0	0	0.1	0.3	0.7	1.2	1.9	2.9	3.6	4.5	5.3	6.8	8.4	8.7	8.4	8.8	7.4	7.8	6.3	16.9
50m	0	0	0.1	0.2	0.5	1	1.6	2.4	3.2	4.1	4.7	5.6	6.9	8	7.7	7.8	6.9	6.9	7.6	24.8
70m	0	0	0.1	0.3	0.6	1.1	1.8	2.7	3.9	4.9	5.9	6.9	8.6	8.6	9	8.5	7.8	8.8	6.8	13.7

Table 4-4 2005 percentage of occurrence for energy

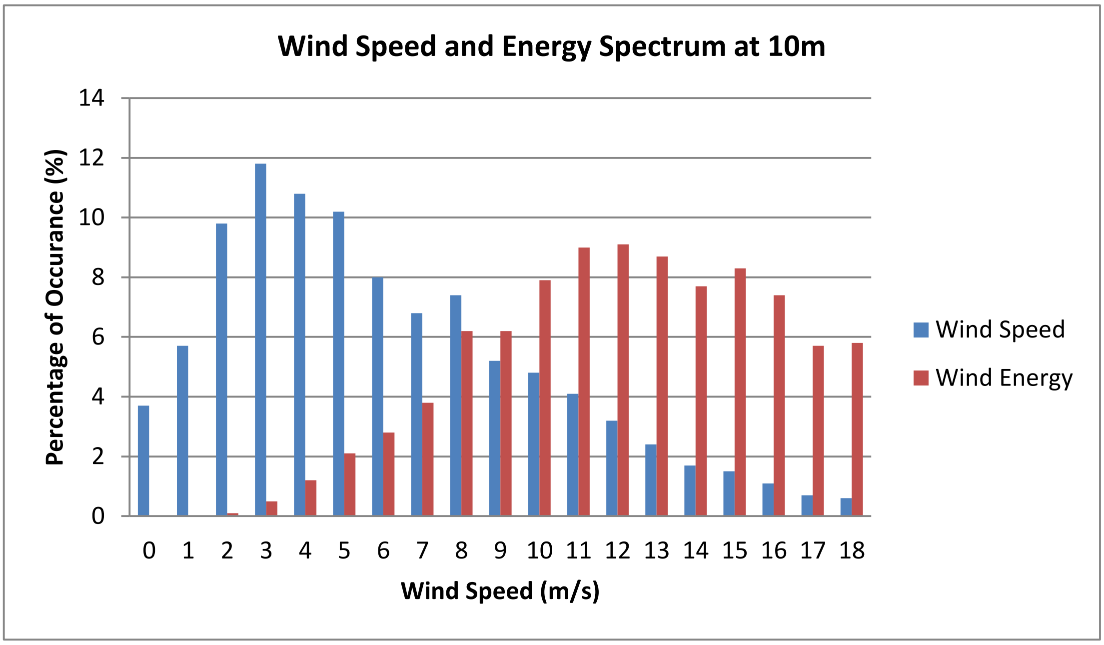


Figure 4-4 Wind speed and energy spectrum at 10m height

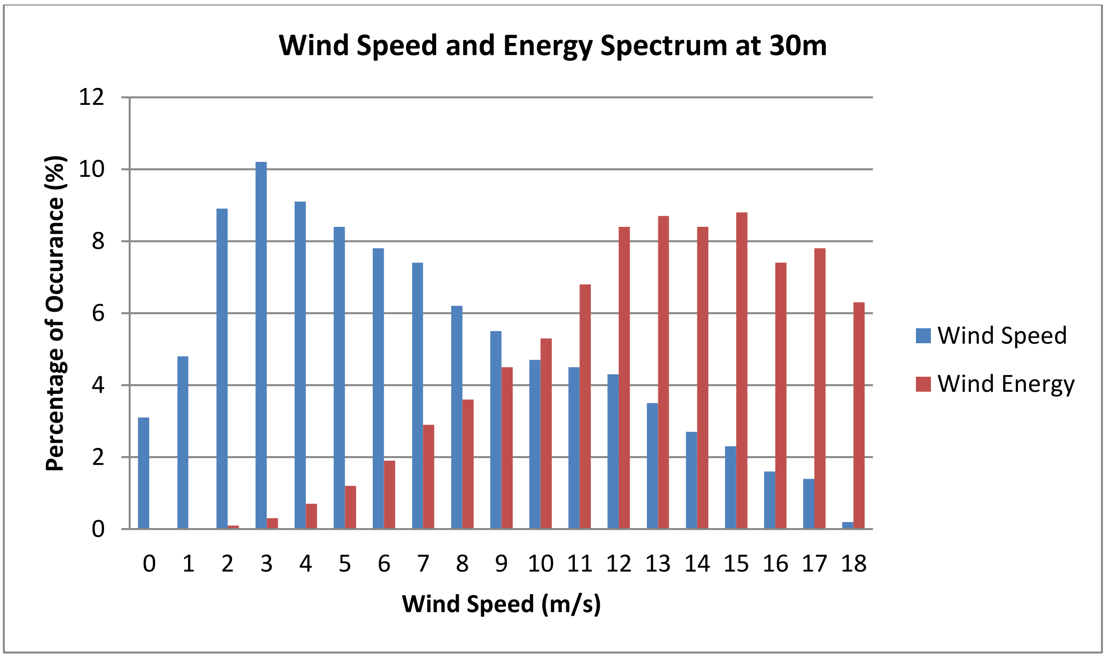


Figure 4-5 Wind speed and energy spectrum at 30m height

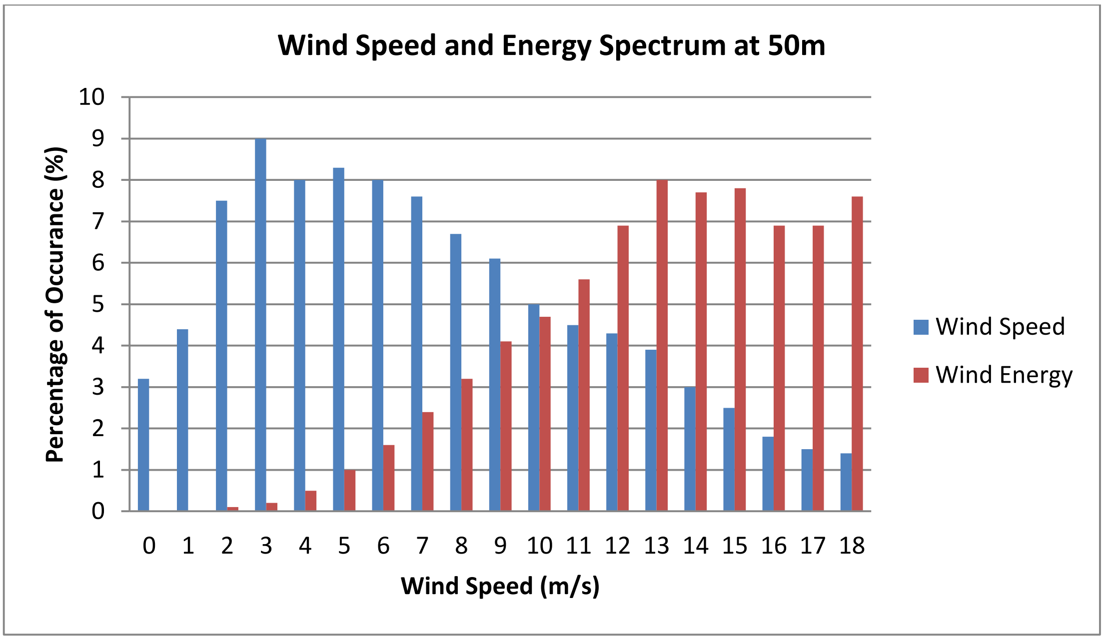


Figure 4-6 Wind speed and energy spectrum at 50m height

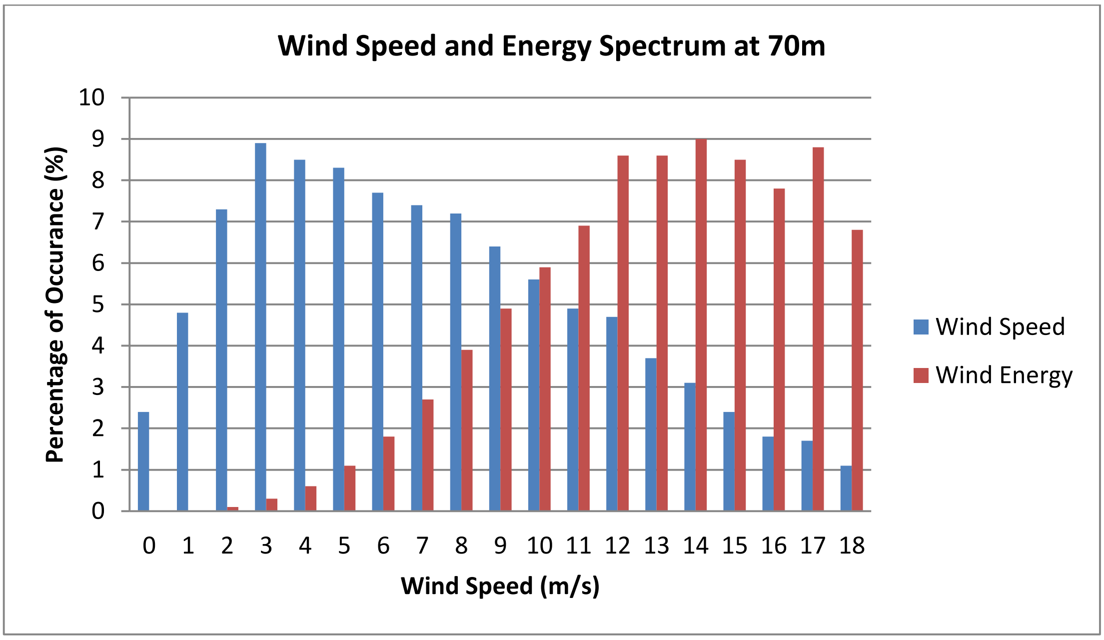


Figure 4-7 Wind speed and energy spectrum at 70m height

Based on manufacturer's calculation and experience, the designated project site has efficiency of 92% with the consideration of energy lost from the system in this particular wind farm site. The overall effect of different aspect on wind turbine losses are illustrated in Table 4-5.

	Air Density	**Wake Effect**	**Availability**	**Blade Efficiency**	**Turbulence intensity**	**Power Lost**	**Overall Efficiency**
%	95%	94%	96%	98%	98%	92%	76%

Table 4-5 Reference data from wind farm in the case study

5. Energy Simulation

The WECS proposed in this research study is as shown in Figure 5-1. The wind kinetic energy captured in the wind turbine drives a rotor that is mechanically coupled to the SCIG. The SCIG is configured to operate as a fixed-speed generator and utilizes variable external capacitors connected at its terminals for excitation. The capacitors are sized to provide a maximum of no load reactive power requirement of the induction generator to avoid over excitation. The SCIG is grid-connected without any power electronic converter and hence the grid governs a fixed voltage and fixed frequency operating point of the SCIG that can only run with a limited rotor speed variation (defined by the slip). The voltage variation is compensated by the tap changing transformer, which is considered as an AC-AC converter that keeps the grid side voltage within acceptable fixed limits. As the capacitors' value increases/decreases, the stator terminal voltage of the SCIG also increases/decreases. This will be compensated by changing the OLTC settings. The variable capacitors and tap changing transformer will be controlled through a supervisory control system to achieve maximum power transferred to the grid and maintain the grid side voltage and frequency at acceptable limits.

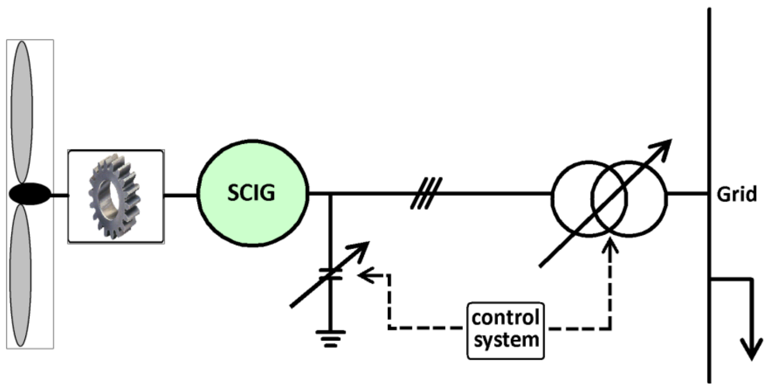


Figure 5-1 Schematic diagram of the proposed model

The operating points of the fixed speed wind energy system are defined by the intersection points between the torque speed or power-speed curves of the induction generator and the wind turbine. For every wind speed there is a corresponding curve that characterises the operation of the wind turbine at that particular speed. However, instead of these curves intersecting a single induction machine curve as in conventional system, in the proposed system, the stator terminal voltage varies resulting in the shift of the power speed curve. For maximum optimal power to be obtained within the limitation of the fixed speed induction generator, ideally both the stator terminal voltage and rotor speed should be set to maximum. However, these two are interdependent in an inverse relation manner. Moreover, the speed of the induction generator is limited by the slip and the stator voltage is limited by the operating range of the OLTC transformer. To explain the relationship between the terminal voltage of the induction generator and rotor speed, firstly the inertia equation has to be investigated.

So load torque is affected by the turbine rotor speed, which is mechanically coupled to the rotor of the induction generator through a gearbox. Assuming that the system is a lossless system with power produced by the wind turbine directly conveyed to the rotor of the induction generator, the power at the rotor of the induction generator that can be conveyed to the grid is defined by implementing this equation verifies the inverse relationship between rotor speed and stator voltage. Due to this inverse relationship it is impossible to maximise both speed and voltage of improvement in power transfer, instead there exist an operating point where the combination of speed and voltage at that point will result in more efficient energy transfer than any other point.

Moreover, in contrast to a single operating point that will be adopted by the conventional system at a particular wind speed, with the proposed system, the operating point can be shifted to another more beneficial position to improve the power transfer. Thus, as long as the original operating point is not the optimal operating point within the allowable operating region of the proposed system, the implementation of the proposed system will improve the power that can be transferred to the grid.

The SCIG has torque-slip characteristic as shown in Figure 5 2. The system is intended to operate in the fixed speed region of between -0.05% to -4%

(1501rpm – 1560rpm for a 4 poles SCIG connected to 50Hz grid). The key for significant gain is the high slope of the induction generator's torque-speed curve in this operating region. The terminal voltage of the SCIG is intended to vary between 10% of the rated voltage.

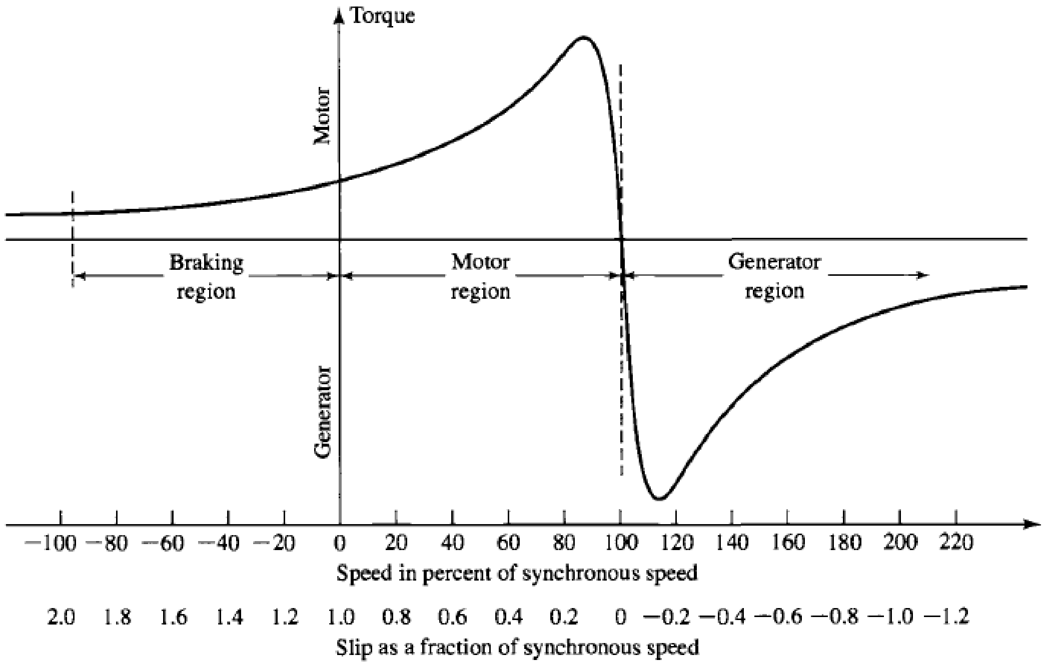


Figure 5-2 Torque-slip characteristic of an Induction Machine [20]

An induction machine can work as a generator if the required amount of reactive power is supplied to sustain the excitation requirement, while the rotor speed is maintained by some prime mover above the synchronous speed. When the generator is connected to the grid, theoretically, it is possible for this reactive power requirement to be supplied by the grid. However, due to the connection regulation, it is required that at the point of common coupling a certain power factor is maintained. This means that the generator is not allowed to take reactive power from the grid and have to be self-sufficient through the utilization of excitation capacitors. Utilising squirrel-cage induction machine as self-excited induction generator is beneficial as it has high power density and simple construction. Furthermore, the self-excitation characteristics causes the voltage to collapse rapidly when overloaded, thus providing self-protection.

Transformer with tap changer acts to maintain the grid side voltage within its permissible limits despite any voltage variation on the generator side due to changing in the excitation level or any load changes. Authors of this research project have proved in a previous study [48] that OLTC can improve power transfer capability of power systems. This power depends on the tap settings, load type and level of capacitor compensation. Figure 5-3 shows the system proposed in this study.

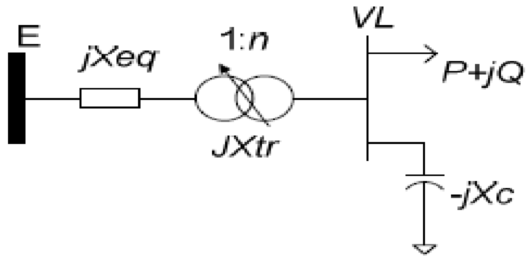


Figure 5-3 Simplified power system with OLTC and capacitor-compensated load

Figure 5-4 shows the effect of different static load models namely; constant impedance (CZ), constant current (CI) and constant power (CP) on the power transfer to the load at different OLTC settings. It can be seen from Fig. 5-4 the load model and OLTC tap settings significantly affect the power transfer to the load centre. In all cases, the power transfer is increased by increasing the OLTC tap settings, when optimum power is reached; further increase in OLTC settings will decrease power transfer to the load.

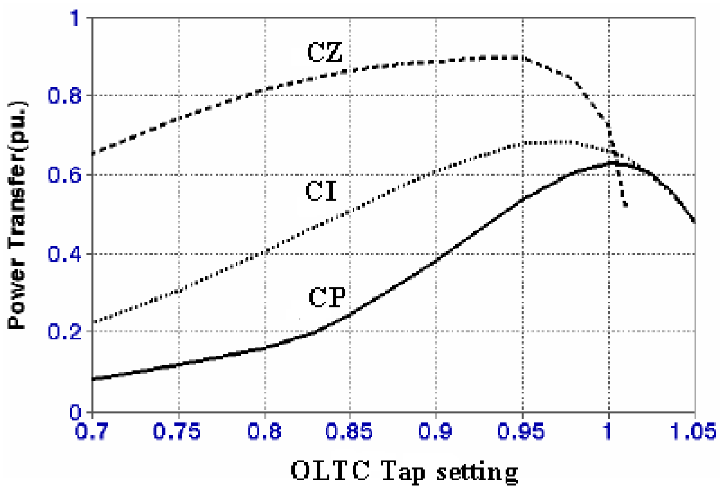


Figure 5-4 Power transfer as a function of transformer tap ratio

Figure 5-5 shows the capacitor compensation effect on the power transfer limit to a constant current load at different OLTC tap settings. The maximum power limit for uncompensated load (XC= ∞) is 0.5pu while in case of little compensation (XC=10pu), the maximum power is 0.62pu. It can be concluded that The shunt capacitor increases the power transfer limit and shifts the optimal setting of OLTC to a higher value. Thus the maximum power transfer limit to a compensated load can be increased by either adjusting the tap ratio of OLTC or by increasing the degree of compensation. The power increase is attributed to the fact that the OLTC tap settings allow the match between the network impedance and the reflected compensated load impedance.

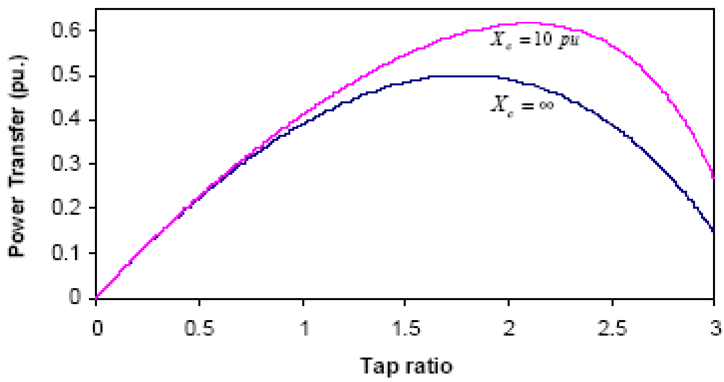


Figure 5-5 Effect of compensation and OLTC setting on Power transfer to CI load

The above methodology will be used to develop a control algorithm to control the OLTC settings and the excitation level in the proposed WECS to maximise power transfer from the induction generator to the grid subject to all other constraints such as maintaining the terminal voltage and frequency within their permissible limits. The WECS is proposed to operate in a small window of fixed speed region as shown in Figure 5-6 by the shaded area. The turbine output power is computed using the data from Vestas V82-1.63MW wind turbine specification [49]. The dashed horizontal lines in Figure 5-6 shows that by controlling the stator terminal voltage it is possible to move the point of operation at any particular wind speed [50].

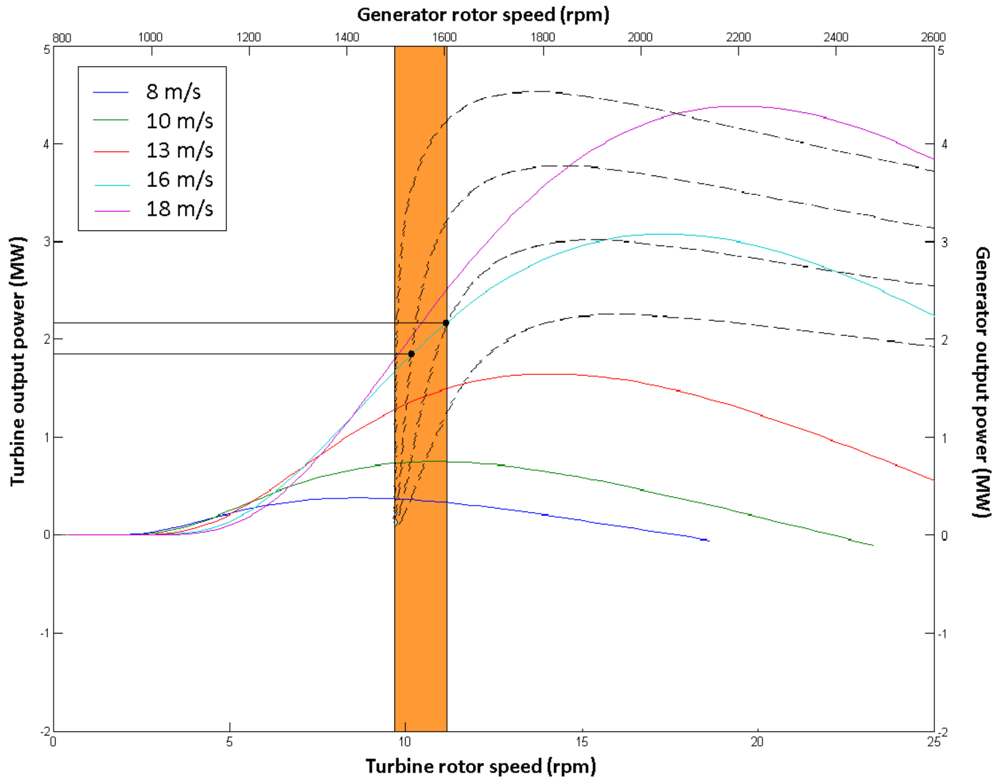


Figure 5-6 System Operation Region

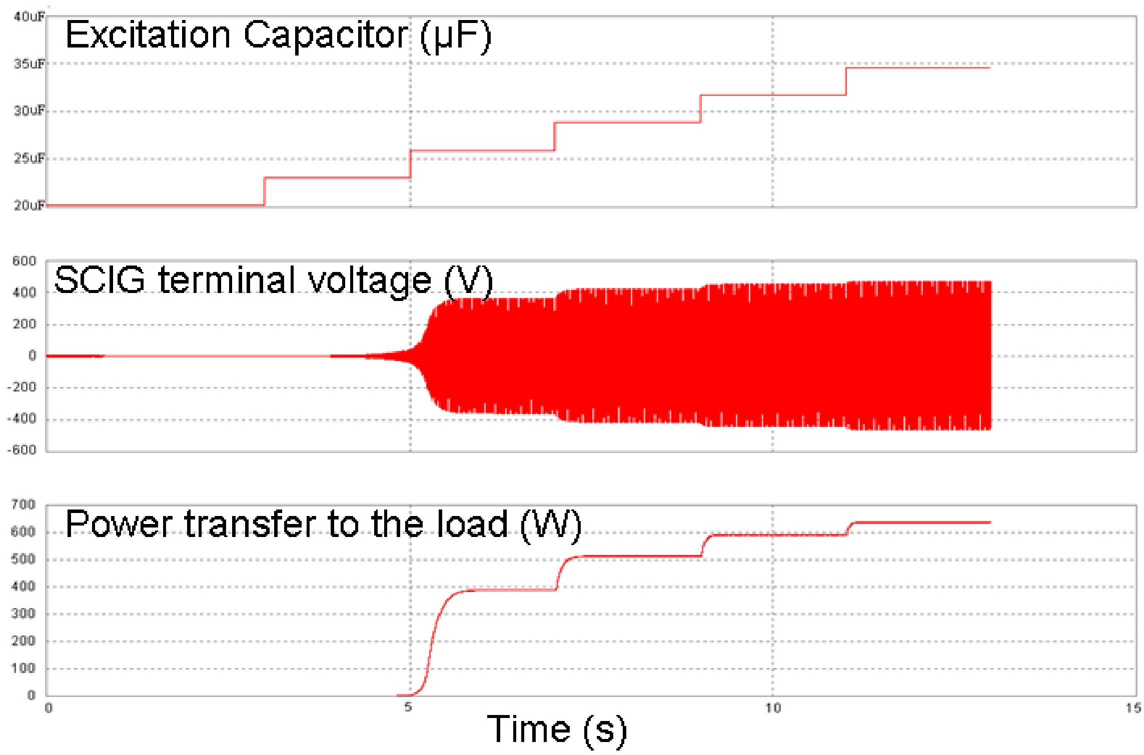


Figure 5-7 PSIM Simulation Results

Within the tolerable fixed speed region, output power can be significantly improved by adjusting the terminal voltage obtained by varying the excitation capacitors. The key here for significant gain is the high slope of the induction generator's torque-speed curve as shown in Figure 5-6. The method of stator terminal adjustment to vary output power and generator torque for stand-alone application can be found in [51]. Simulation of a self excited SCIG operating without connection to the grid has been performed on PSIM software. The simulation was performed by running a mathematical model coded in C++, built in Borland and integrated with the object-oriented load module in PSIM. This was done to ensure the scalability of the model so that various loads can be simulated. A snapshot of the simulation results is shown in Figure 5-7. It can be seen that increasing the excitation capacitors will result in increasing the power transfer to the load as well as the stator terminal voltage.

Simulation of a scalable SCIG operated as a grid-connected IG has been performed on PSIM® simulation platform. The wind turbine is modelled from a 3kW

WestWind turbine specification with power curve shown in Figure 5-8. [52] The simulation model is shown in Figure 5-9. It consists of a wind turbine model directly coupled with a SCIG through a gearbox, as well as a capacitor bank, a transformer and a grid, modelled by a three-phase voltage source. The realization of tap-changing transformer is not included in this preliminary modelling of the system and the turn ratio of the transformer is changed manually for every simulation performed.

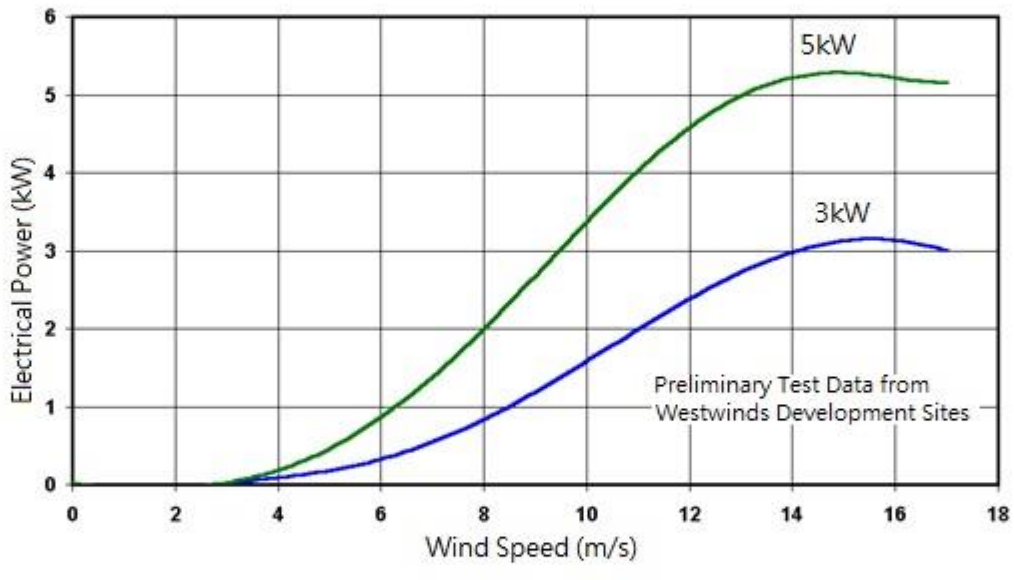


Figure 5-8 Westwind 3kW Wind Turbine Power Curve [52]

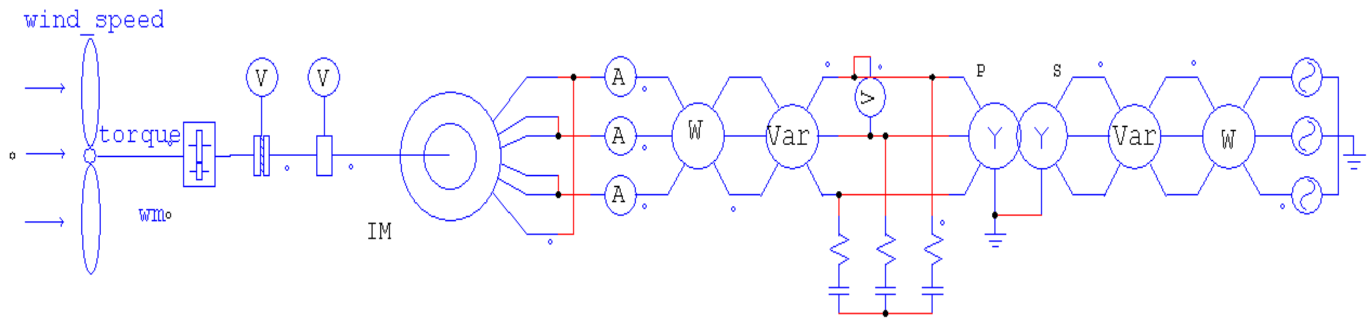


Figure 5-9 PSIM simulation model

In PSIM, an SCIG generates power when supplied by a negative torque on its shaft. Due to the placement direction of the meters, power is negative when generated by the SCIG and positive when consumed by the SCIG. The gearbox is tuned to optimize the operation at a wind speed of 8m/s, which will make Cp value ranging at 0.45. The SCIG has a rated voltage at 220V and a base turn ratio of 1:2 is used for the transformer.

A snapshot of a simulation result is shown in Figure 5-10 and Figure 5-11. From these figures, it can be seen that after an approximately 0.4s initialization period, the turbine model supplies negative torque to the SCIG, which in turn generates real power to the grid and consumes reactive power from the grid.

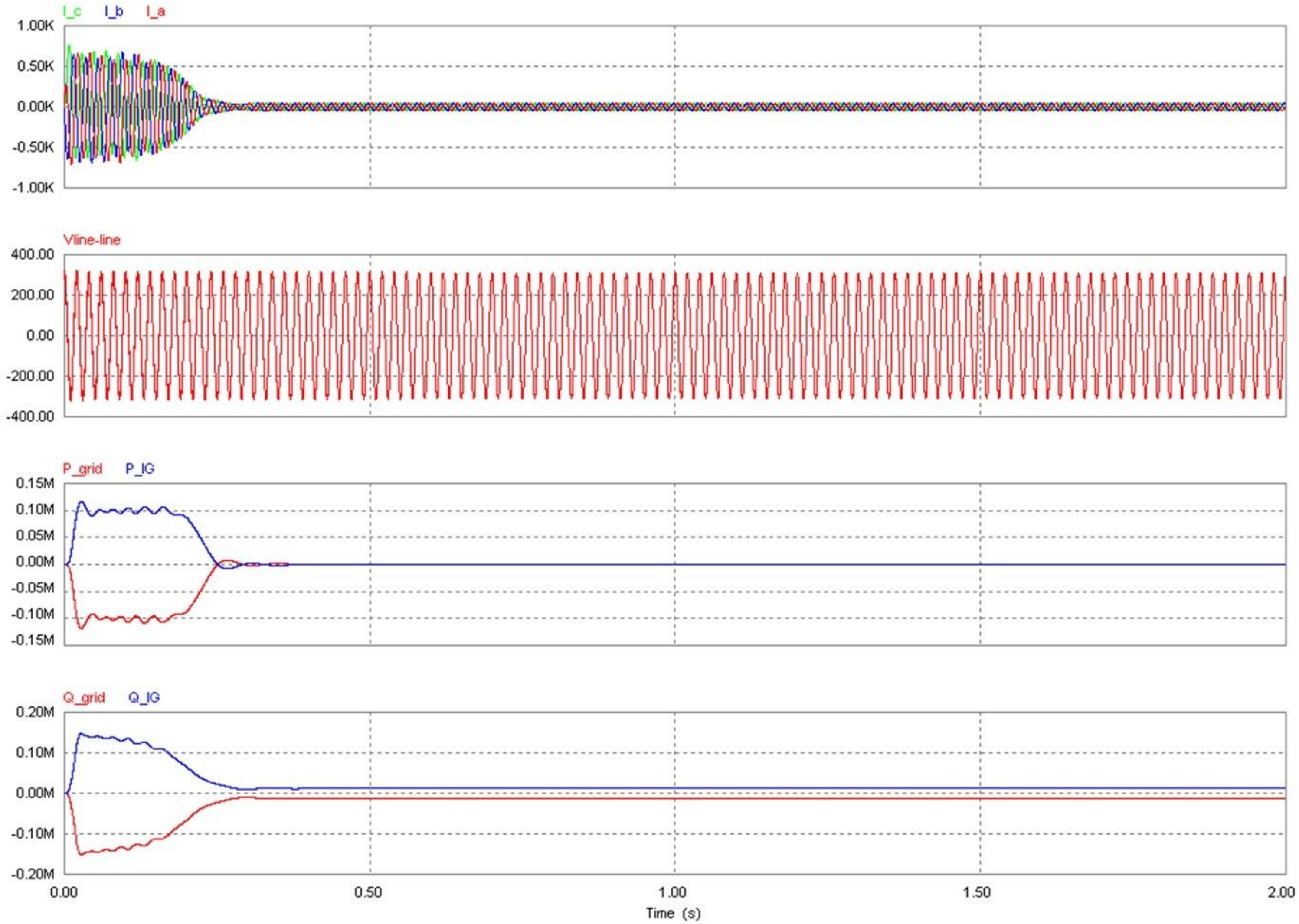


Figure 5-10 PSIM Simulation Results showing the Initialization and Power Transfer of the System

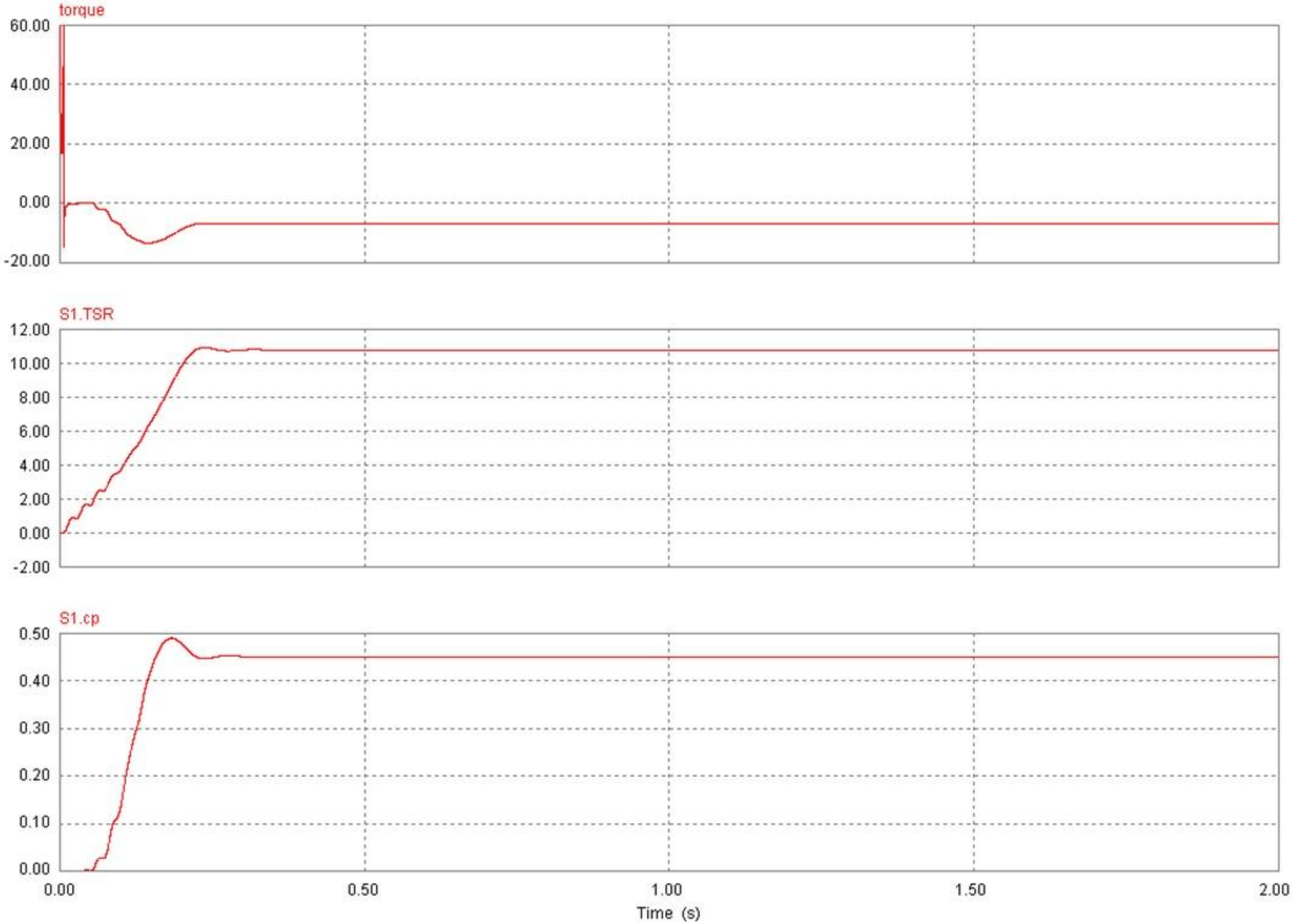


Figure 5-11 PSIM simulation results showing the negative torque, Tip Speed Ratio (TSR) and cp

A partial hardware testing was performed on a three-phase, 4 poles, 2.2 kW induction machine running as a self excited induction generator to validate the simulation results. Switched shunt capacitor is utilized to provide various level of reactive power to excite the SCIG. Figure 5-12 shows the results obtained by loading the system with resistive loads. The rotor speed was kept at 1545 rpm, which is corresponding to a 3% slip (within the region of fixed speed operation). Figure 5-12 shows that by increasing the excitation capacitors, terminal voltage increases and more power can be transferred to the load.

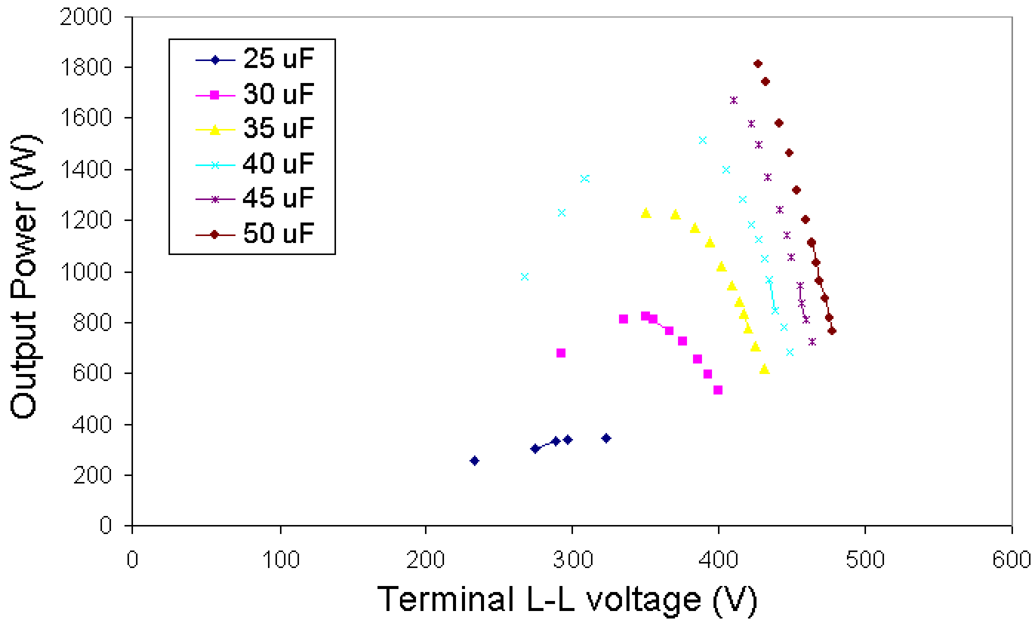


Figure 5-12 Results at Generator Rotor Speed of 1545rpm

The above results show that the utilization of variable capacitors and tap changing transformer can significantly improve the power transfer capability of a WECS with fixed speed SCIG. A global controller that can control the value of excitation capacitor as well as the tap position of the transformer can be further investigated in the future.

6. Energy Simulation Results for the Test System

6.1 Model Verification

To provide verification to the proposed simulation model, data from an operational wind farm utilising the 750kW wind turbine is used. This wind farm is located in China with 900m elevation above sea level and is equipped with 66 wind turbines to have the total capacity of 49.5MW. The average temperature is 6.5 Degrees Celsius with the average pressure being 152.5kPa.

The wind turbine is a three bladed with 750kW rated capacity and has a rotor diameter of 48m with a swept area of 1886m^2 (including the area of the hub). The generator is rated at the same rated power of 750kW with frequency of 50Hz and rated voltage of 690V. The rated rotational speed of the generator is 1520rpm. The wind resource analysis from the farm reports that the 70m hub height average annual wind speed is 7.9m/s and the effective operating hour of the wind turbine is above 6000 hours in a year. This is an above 68% annual operational percentage for the wind farm.

The average wind speed at different hub height of the site is shown in Table 6-1. The wind farm is connected to 110kV grid connection point through a main transformer with the capacity of 50MVA.

Hub height (m)	Average wind speed (m/s)
10	6.5
30	7.4
50	7.9
70	7.9

Table 6-1 Average wind speed at different hub heights

To verify the model, it is compared to data from turbine manufacturer. The simulation model must try to closely emulate the power curve or the steady state behaviour of the real wind turbine.

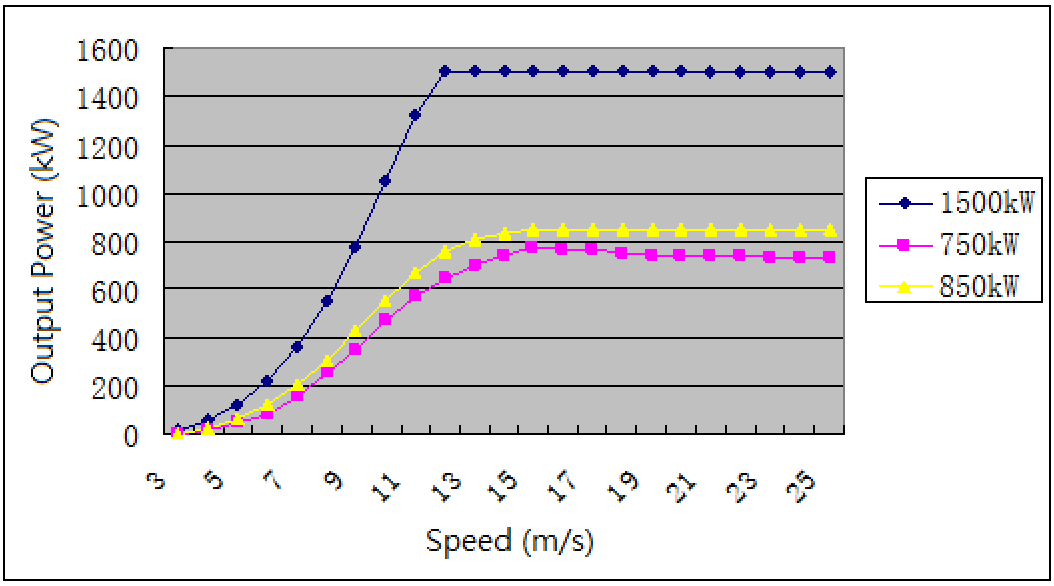


Figure 6-1 The power curve for the wind turbine published by manufacturer

Stator resistance (Rs)	0.013 Ω
Stator inductance (Ls)	0.3503 mH
Rotor resistance (Rr)	0.01718 Ω
Rotor inductance (Lr)	0.3949 mH
Magnetising inductance (Lm)	24.84 mH
Inertia (J)	7.8 kgm2

Table 6-2 Parameters from the actual wind turbine given by the manufacturer

Wind Speed (m/s)	Cp	Thrust Coefficient	Power Data from Real Wind Turbine (kW)
4	0.190838	1.22137	12.9773
5	0.359223	1.07417	47.7159
6	0.428127	0.968511	98.2639
7	0.456555	0.883695	166.403
8	0.466093	0.81261	253.576
9	0.460995	0.746488	357.109
10	0.439844	0.677434	467.383
11	0.40402	0.605723	571.423
12	0.354901	0.533662	651.668
13	0.304329	0.468056	710.462
14	0.255296	0.4111	744.395
15	0.211757	0.362553	759.43
16	0.175088	0.322761	762.062
17	0.144288	0.289957	753.274
18	0.119389	0.263098	739.873
19	0.099316	0.240705	723.861
20	0.083333	0.221837	708.406
21	0.070562	0.205791	694.394
22	0.060452	0.192212	684.005
23	0.052458	0.180716	678.219
24	0.046046	0.17087	676.403
25	0.040872	0.162333	678.617

Table 6-3 Wind data from the actual 750kW wind turbine used

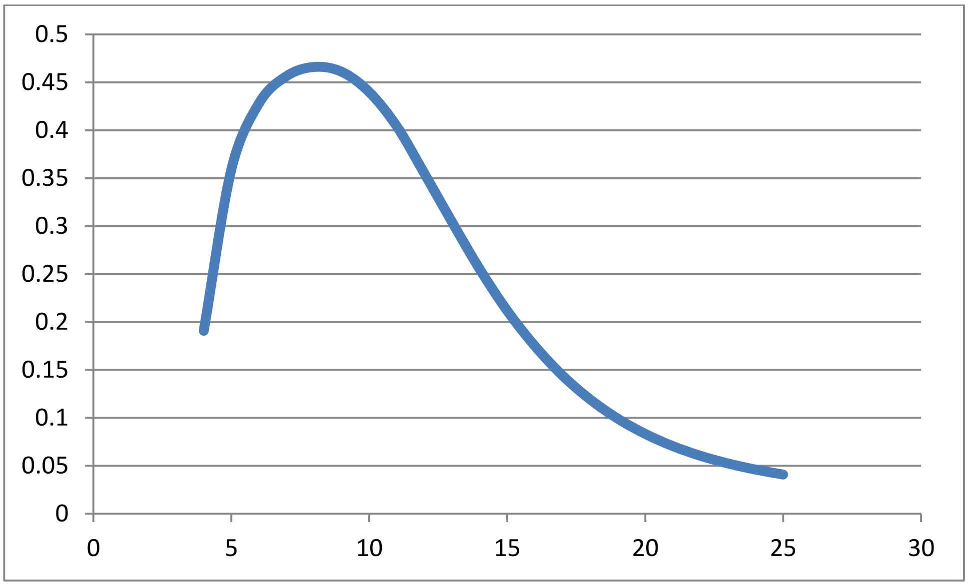


Figure 6-2 Manufacturer provided Cp lambda curve

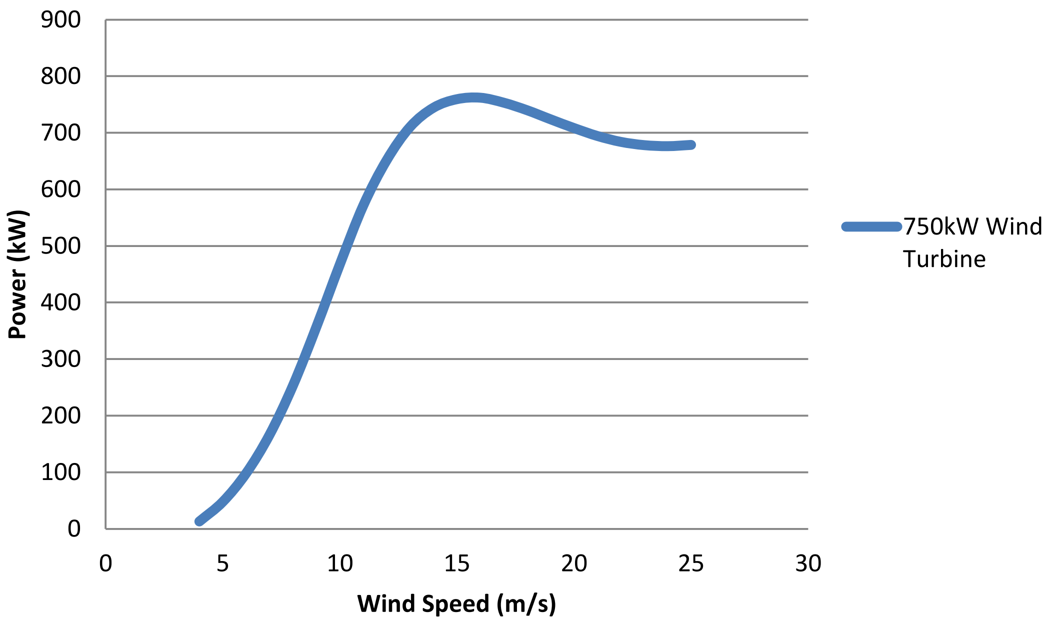


Figure 6-3 Generated power curve based on test by the manufacturer

Wind Speed (m/s)	Real Power Data from Wind Turbine (kW)	Power Curve Data (W)	Difference (%)
4	12.9773	12.6	3.150
5	47.7159	47.2	1.011
6	98.2639	98.0	0.283
7	166.403	166.2	0.107
8	253.576	253.2	0.133
9	357.109	356.3	0.217
10	467.383	466.2	0.258
11	571.423	570.1	0.238
12	651.668	651.3	0.055
13	710.462	710.9	-0.060
14	744.395	746.4	-0.266
15	759.43	762.9	-0.460
16	762.062	766.8	-0.625
17	753.274	759.6	-0.845
18	739.873	747.2	-0.988
19	723.861	731.9	-1.114
20	708.406	716.8	-1.178
21	694.394	702.8	-1.214
22	684.005	692.1	-1.179
23	678.219	685.6	-1.094
24	676.403	683.2	-0.998
25	678.617	684.6	-0.879

Table 6-4 Wind data comparison between the actual and simulated wind turbine

The turbine power limiting control strategy is done through passive stall of the turbine's 3 blades and is equipped with a squirrel cage induction generator. This data is depicted in Table 6-3. To further illustrate the data, the Cp has been plotted against tip speed ratio in Figure 6-2 and its power has been plotted against wind speed in Figure 6-3.

Emulating this turbine in a Simulink model the power curve in Figure 6-4 can be obtained. In Figure 6-4, the simulated results are shown as compared to the manufacturer's power curve.

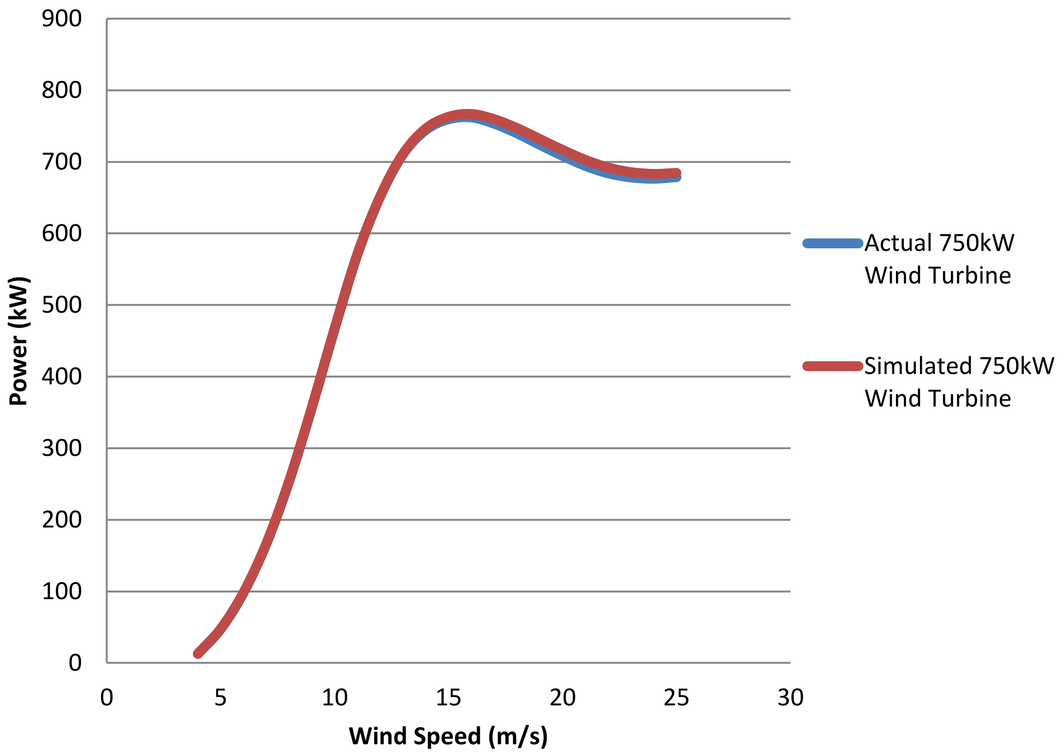


Figure 6-4 Power curve comparison

As can be seen from Figure 6-4, the difference between the two curves are very small with average deviation of less than 1%. The biggest deviation is seen on the low wind speeds as power produced at these wind speed are lower and hence resulting in small denominator when percentage is calculated.

Wind Speed (m/s)	Hours	Proposed Power (kW)	Original Power (kW)	Proposed Energy (kWh)	Original Energy (kWh)
0	0	0	0	0	0
0.5	70	0	0	0	0
1	138	0	0	0	0
1.5	203	0	0	0	0
2	263	0	0	0	0
2.5	317	0	0	0	0
3	365	0	0	0	0
3.5	404	0	0	0	0
4	434	10	9	4133	4126
4.5	457	23	23	10514	10514
5	470	42	42	19638	19624
5.5	475	63	63	29988	29960
6	473	89	89	42208	42139
6.5	464	119	118	54985	54892
7	448	153	153	68509	68357
7.5	427	191	190	81621	81424
8	403	234	233	94191	93926
8.5	375	280	279	104927	104608
9	345	330	329	113861	113447
9.5	314	381	380	119727	119328
10	283	434	432	122692	122214
10.5	252	486	485	122431	122059
11	222	536	534	118970	118592
11.5	194	583	581	113029	112705
12	168	621	619	104169	103824
12.5	144	658	655	94371	94028
13	122	686	683	83481	83150
13.5	102	712	709	72719	72407
14	85	729	726	61961	61684
14.5	70	743	739	52045	51801
15	57	751	748	43004	42800
15.5	46	756	753	35034	34864
16	37	760	756	28218	28080
16.5	30	759	755	22401	22293
17	23	757	753	17602	17518
17.5	18	751	747	13632	13568
18	14	746	743	10490	10440
18.5	11	738	735	7960	7925
19	8	732	729	6006	5978

19.5	6	723	720	4473	4453
20	5	717	714	3313	3299
20.5	3	709	706	2427	2417
21	3	703	700	1767	1760
21.5	2	695	692	1274	1269
22	1	690	687	913	910
22.5	1	685	682	649	646
23	1	681	679	458	456
23.5	0	678	676	321	320
24	0	677	674	224	223
24.5	0	676	673	155	154
25	0	676	673	106	106
Total				1890597	1884288

Table 6-5 Annual Energy Production of the proposed and original system

In Table 6-5, it shows the per turbine annual energy production of the proposed and original system. There is an increase of 6349.43 kWh or 6.35MWh annual energy productions per turbine. In the site of Dacheng wind farm, 66 of the 750kW turbines are installed. Multiplying this increase with the number of turbines will result in a total increase of 416.4 MWh for the wind farm in a year. This is a significant improvement that can lead to a significant financial advantage. With a typical household consuming 4000kWh per year, the improvement in power transfer can be utilized to power a neighbourhood of around 100 households.

The possible improvement in energy production of the proposed system at the same site with different mean wind speed ranging from low 4m/s to high 10m/s is shown in Table 6-6. It was found that the proposed system is capable of improving this energy production by around 0.2% to more than 0.3%.

The utilization of variable capacitors and tap changing transformer in tandem can improve the power transfer capability of a WECS with fixed speed SCIG, within a tolerable window opportunity. Only minor modification, in the form of a global controller that will control the values of excitation capacitor as well as the tap position of the transformer, needs to be added to the existing system. It was found that annual energy production of the WECS can be improved and this improvement can be significant especially when the proposed system is implemented in a large system, which is normally the case for a fixed speed WECS. Further investigation is being undertaken by the authors to decide on the most optimum control solution for the proposed system.

Average Wind Speed (m/s)	Proposed Energy (MWh)	Original Energy (MWh)	Gain in Energy (MWh)	% Improvement
4	249	249	0.47	0.19
4.5	389	388	0.85	0.22
5	559	558	1.36	0.24
5.5	756	754	2	0.26
6	973	971	2.75	0.28
6.5	1206	1203	3.59	0.3
7	1448	1444	4.52	0.31
7.5	1694	1689	5.5	0.33
8	1939	1933	6.51	0.34
8.5	2179	2172	7.54	0.35
9	2410	2402	8.56	0.36
9.5	2631	2621	9.55	0.36
10	2837	2827	10.49	0.37

Table 6-6 The possible improvement of the proposed system at site

7. Conclusions and Further Research

The utilization of variable capacitors and tap changing transformer in tandem can improve the power transfer capability of a WECS with fixed speed SCIG, within a tolerable window of opportunity. Only minor modification, in the form of a global controller that will control the values of excitation capacitor as well as the tap position of the transformer, needs to be added to the existing system. It was found that annual energy production of the WECS can be improved and this improvement can be significant especially when the proposed system is implemented in a large system, which is normally the case for a fixed speed WECS.

Opportunity is available to further extend this research through investigation of the most optimum control criteria and algorithm to implement the tandem variable capacitor and tap changing transformer. This control algorithm can then be implemented as part of a fully automatic prototype, for example on a Raspberry Pi, connected to a virtual WECS to further validate the effectiveness of the research.

Further investigation is also necessary to investigate the effectiveness of this tandem configuration especially in supporting the type A fixed speed SCIG WECS to be compliant to modern grid code that requires reactive and active power control, which could possibly be further enhanced through the utilisation of blade pitch control. This will be useful in making the case for a balanced uninterrupted and maximum energy extraction possible with fault support for the grid.

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